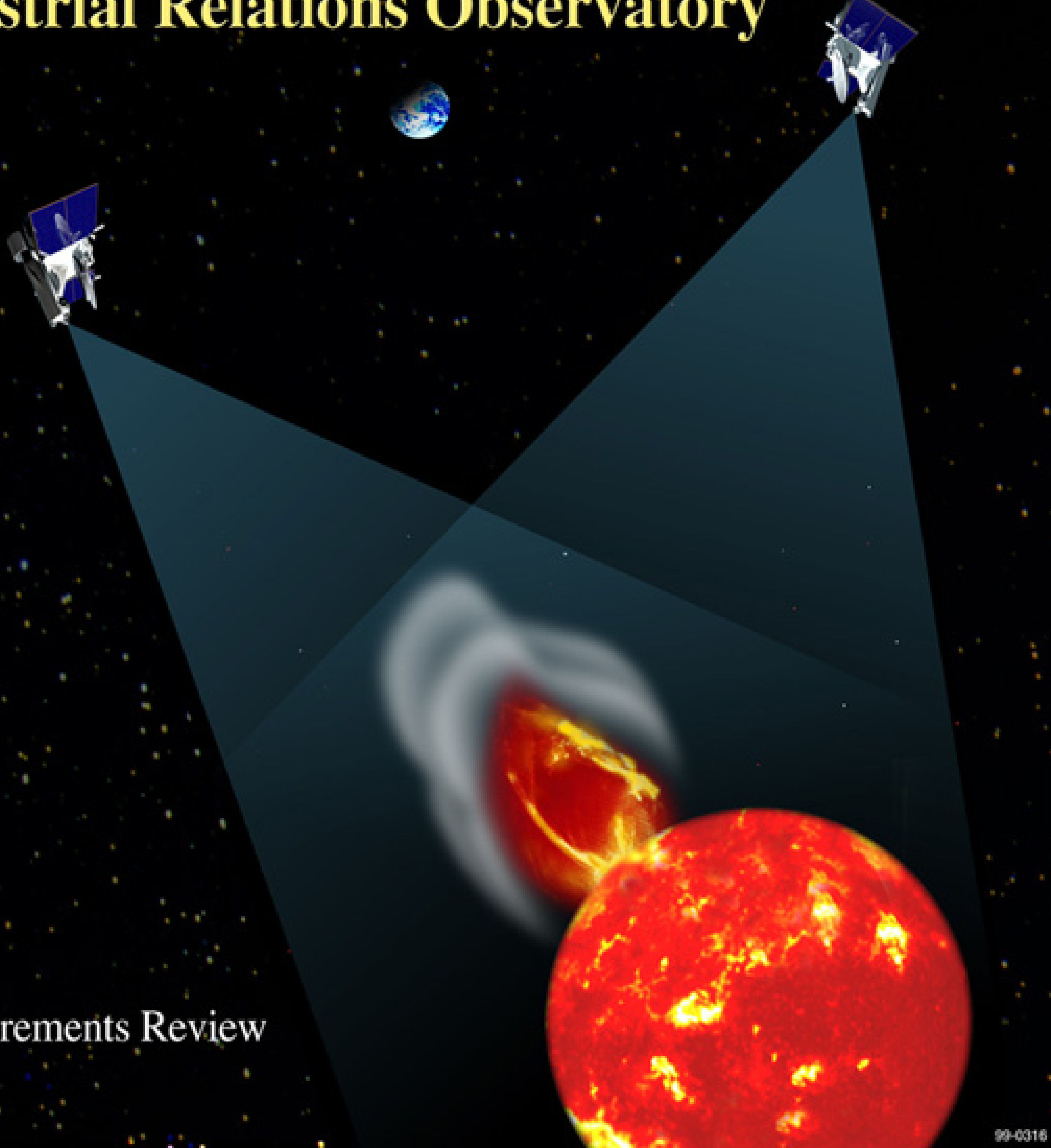
Solar Terrestrial Relations Observatory (STEREO)



Pre-Phase-A Requirements Review
March 5, 1999

Solar Terrestrial Relations Observatory (STEREO)
Pre-Phase-A Requirements Review

PART I of II

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Orbit Determination	G. A. Heyler

Introduction

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Mission

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STEREO Objectives

- Understand the origin and consequences of coronal mass ejections (CMEs)
- Determine the processes that control CME evolution in the heliosphere
- Discover the mechanism and sites of polar energetic particle acceleration
- Determine the 3-D structure and dynamics of coronal and interplanetary plasmas and magnetic fields
- Probe the solar dynamo through its effects on the corona and heliosphere

Implementation Responsibilities

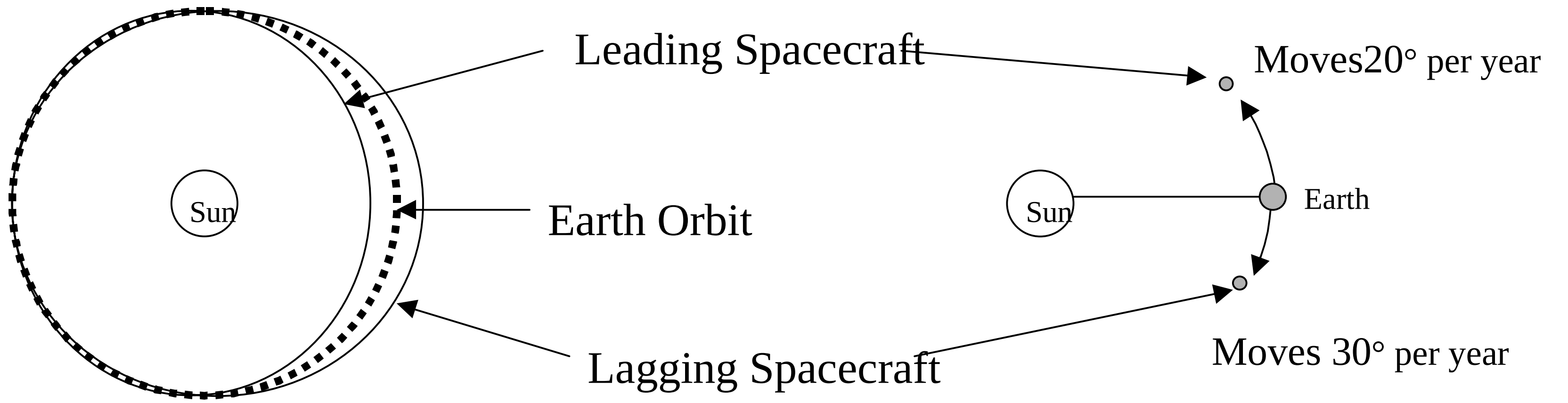
- JHU/APL
  - Provide spacecraft bus, instrument integration, mission design, mission operations, and navigation
  - Manage DSN interfaces
  - Manage spacecraft to instrument interfaces
- GSFC
  - Provide and operate instruments
  - Provide and operate Science Operations Center
  - Launch vehicle procurement

Space Weather Monitoring

- Whenever not in contact with 34-m DSN assets, transmit a low-rate (≈500 bps) science stream that is available to space weather enthusiasts
- All on-board science data processing to be provided by the instruments
- No knowledge of the data content is required by the spacecraft
- A description of the intended ground assets and required downlink rate will be provided by GSFC
- Space weather downlink is not to drive telecommunication design

Mission Design Overview

- One spacecraft orbit less than 1 AU; other orbit greater than 1 AU
- As viewed in a fixed Sun–Earth frame; each spacecraft slowly moves away from Earth



Spacecraft Overview

- Both spacecraft are identical
- 3-axis controlled
- Propulsion for momentum management, no orbit-maintenance requirement
- Single-string with two year primary mission
- Parts/components designed for two year mission duration
- Consumables for five year mission duration
- Design should not preclude extended mission

Operations Overview

- Decoupled spacecraft/ instrument operations
- Daily contacts (seven per week) using 34-m DSN antennas, with the beam-waveguide (BWG) antennas as prime
- Single Mission Operations Center (MOC) to control both spacecraft at JHU/APL
- All operations planning, spacecraft status, and navigation information to be posted on the internet

Spacecraft Operations Concept

- Spacecraft has one operational mode: point at Sun and antennas at Earth
- Thruster firings, used for momentum management, occur at ≈4–10 day intervals
- Most spacecraft operations are autonomous
  - High-gain antenna pointing control
  - Momentum management
  - Power management
  - Thermal management
- On-board recorder management is ground controlled

Instrument Operations Concept

- Instrument operation including health monitoring is a GSFC responsibility, spacecraft operations is a JHU/APL responsibility
- Science team (GSFC) should not need to know any of the details of spacecraft *operation* to plan instrument activity
  - Small time windows budgeted for HGA movement and propulsive events
  - Instrument activity independent of downlink schedule
  - Stored-command memory budgeted for instrument operations
- Spacecraft has resources (power, data bandwidth) to support all instrument activity simultaneously with the only limitation being data volume

Mission Design

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Science Orbit Definition

- Orbit configuration is defined by the desired time history of the spacecraft angular separation
  - Absolute spacecraft separation viewed from the Sun
  - Relative spacecraft separation from the Earth-Sun line
- Desired time history of separation defined by dwell angle and duration from Science Definition Team Report (pg. 30)
    - Leading Spacecraft
      - Drifts ahead of the Earth in its orbit
      - 20° from Earth T = 200 to 400 days
      - 45° from Earth T = 600 to 800 days
    - Lagging Spacecraft
      - Follows behind the Earth in its orbit
      - 30° from Earth T = 200 to 400 days
      - 60° from Earth T = 600 to 800 days

Launch Vehicle Requirements

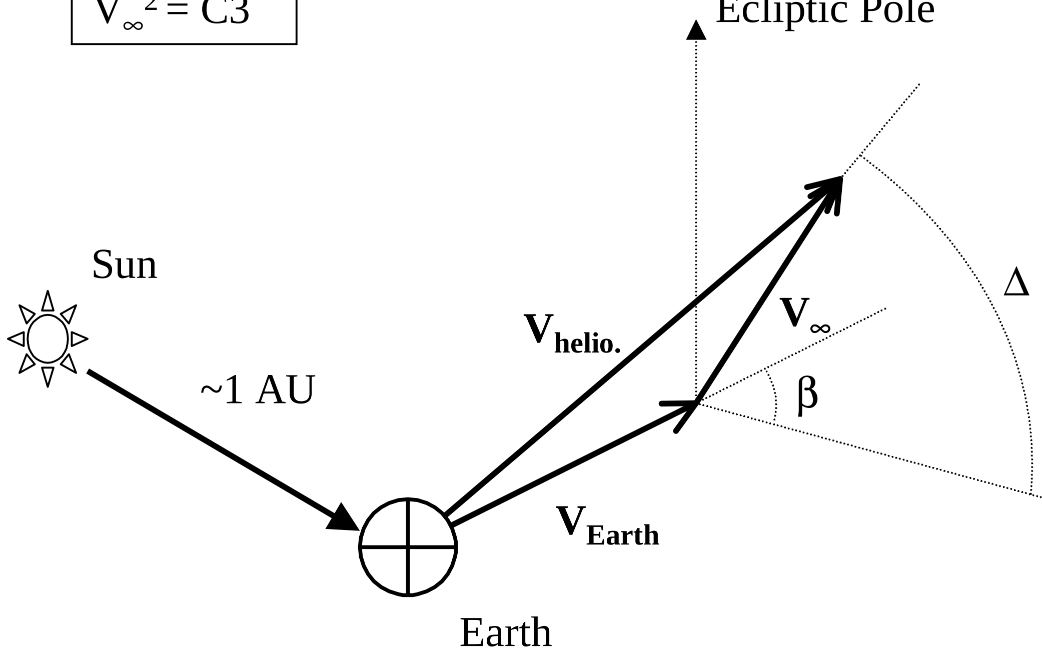
- Launch vehicle provides direct insertion into desired heliocentric orbit
  - Launch energy (C3) requirement limited by launch vehicle and insertion stage motor selection
  - Departure asymptote declination limited by launch vehicle and insertion stage motor selection
  - * No maneuvers by spacecraft to achieve or maintain orbit
- Launch opportunity window (TBD)
- Daily launch window (TBD)

Preliminary Mission Design

- Athena-II Expendable Launch Vehicle
  - 93° Launch azimuth
  - Eastern range (CCAS/KSC) launch site
  - STAR-37 upper stage
  - Preliminary ascent timeline provided by Lockheed-Martin
  - C3 = 1.0 km^2/sec^2
- Launch Dates
  - Leading - October 1, 2002
    - Smallest drift rate ⇒ minimize impact of launch delays for second spacecraft
    - Closer to equinox ⇒ minimize Sun-Probe-Earth angle for RF design
  - Lagging - December 1, 2002

Launch Parameter Definition

$V_\infty^2 = C3$



Preliminary Mission Design (cont'd)

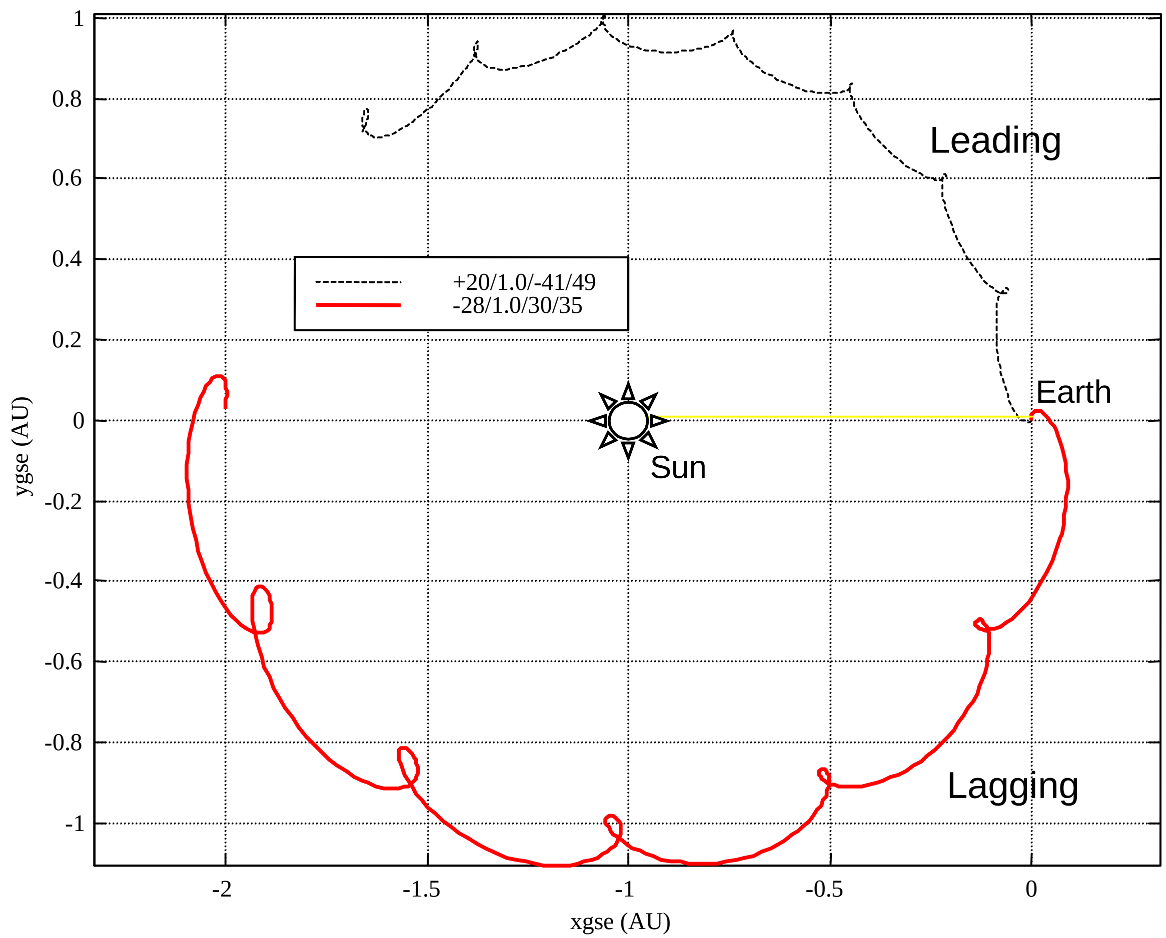
- Leading Spacecraft
  - Design parameters
    - $C3 = 1.0\ km^2/sec^2$, $\beta = -41°$, $\Delta = 49°$
  - $C3 > C3_{min} \approx 0.3\ km^2/sec^2$
    - Reduce sensitivity to launch vehicle dispersions
    - Tailor Sun-Probe-Earth angle characteristics for RF design
  - β selected maximize dwell time at desired separation angle
  - Δ selected to tailor Sun-Probe-Earth angle characteristics for RF design
  - Departure asymptote declination, $\delta = -28°$
    - δ with respect to equator
    - Maximum achievable declination (absolute value) for Athena-II with 93° launch azimuth (maximum launch mass)
  - Mean drift rate relative to Earth-Sun line = 20° per year

Preliminary Mission Design (cont'd)

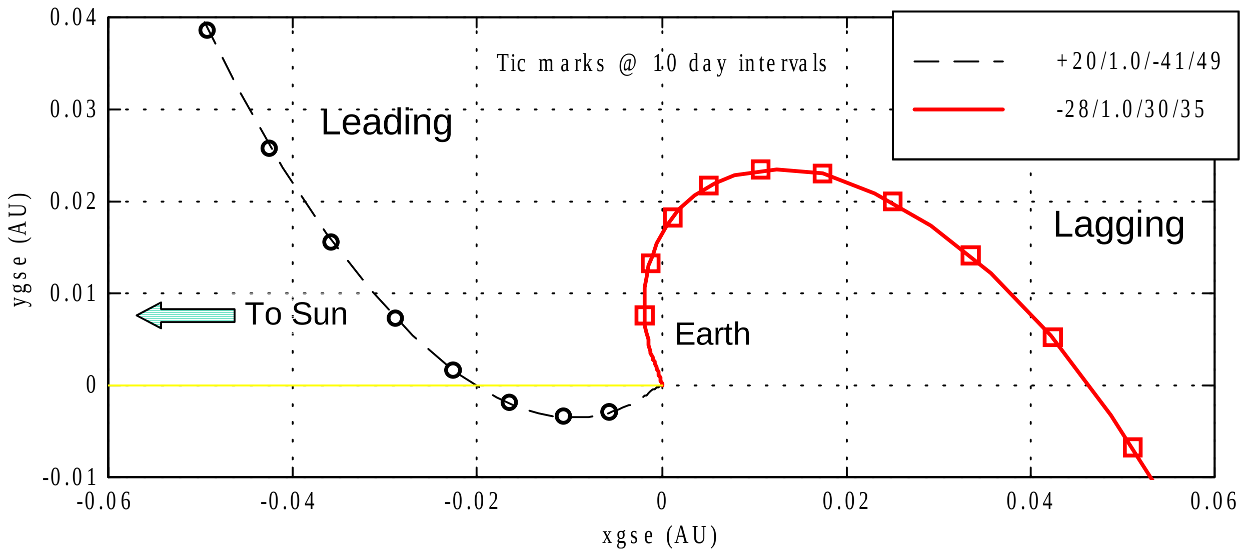
- Lagging Spacecraft
  - Design parameters
    - C3 = 1.0 km^2/sec^2, $\beta = 30°$, $\Delta = 35°$
  - $C3 > C3_{min} \approx 0.6\ km^2/sec^2$
    - Reduce sensitivity to launch vehicle dispersions
  - β, Δ
    - Launch phase definitions identical to leading
    - Impacts to dwell time/separation behavior (TBD)
  - Departure asymptote declination, $\delta = -28°$
  - Mean drift rate relative to Earth-Sun line = 28° per year

STEREO Orbit

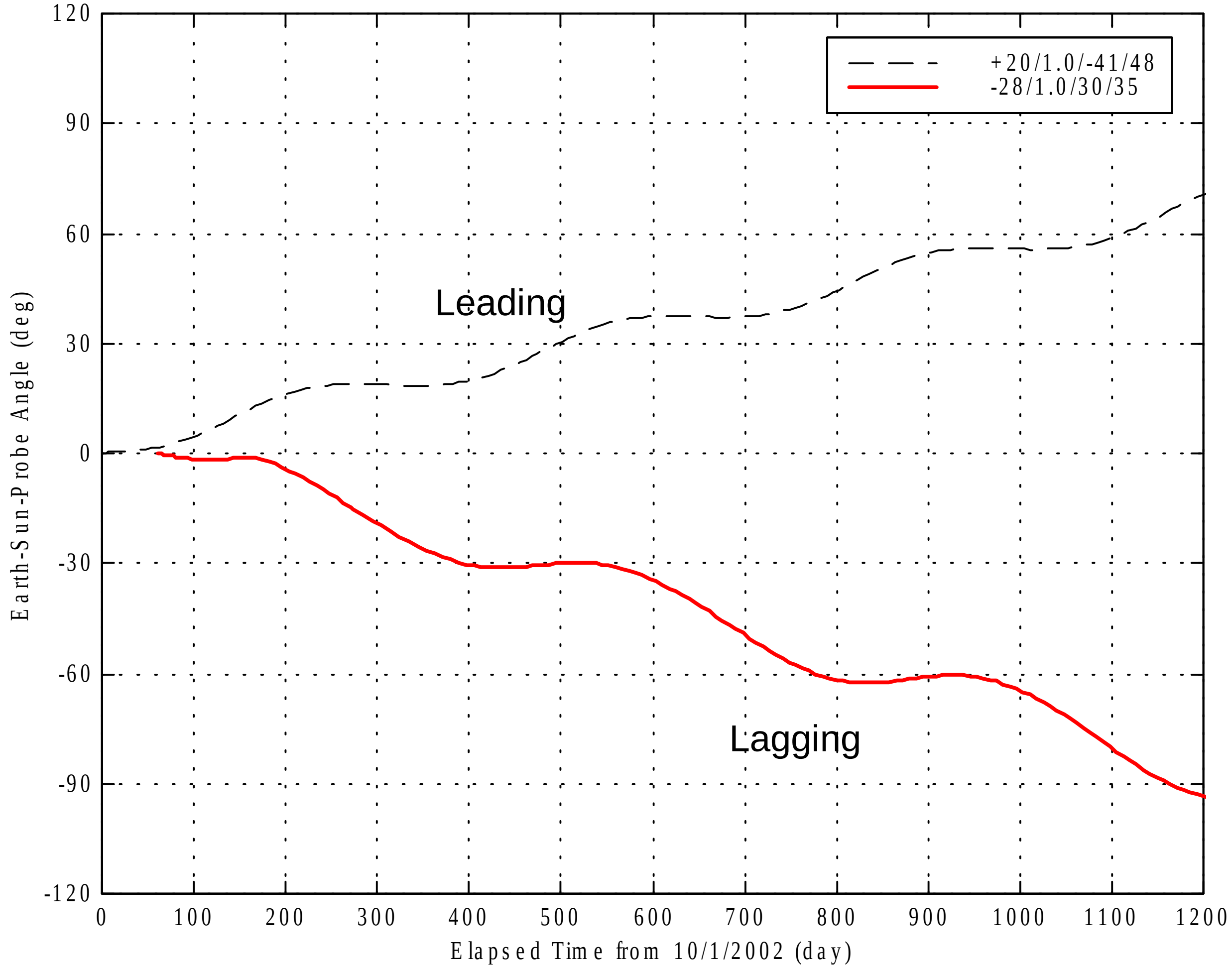
(Geocentric Solar Ecliptic Coordinates)



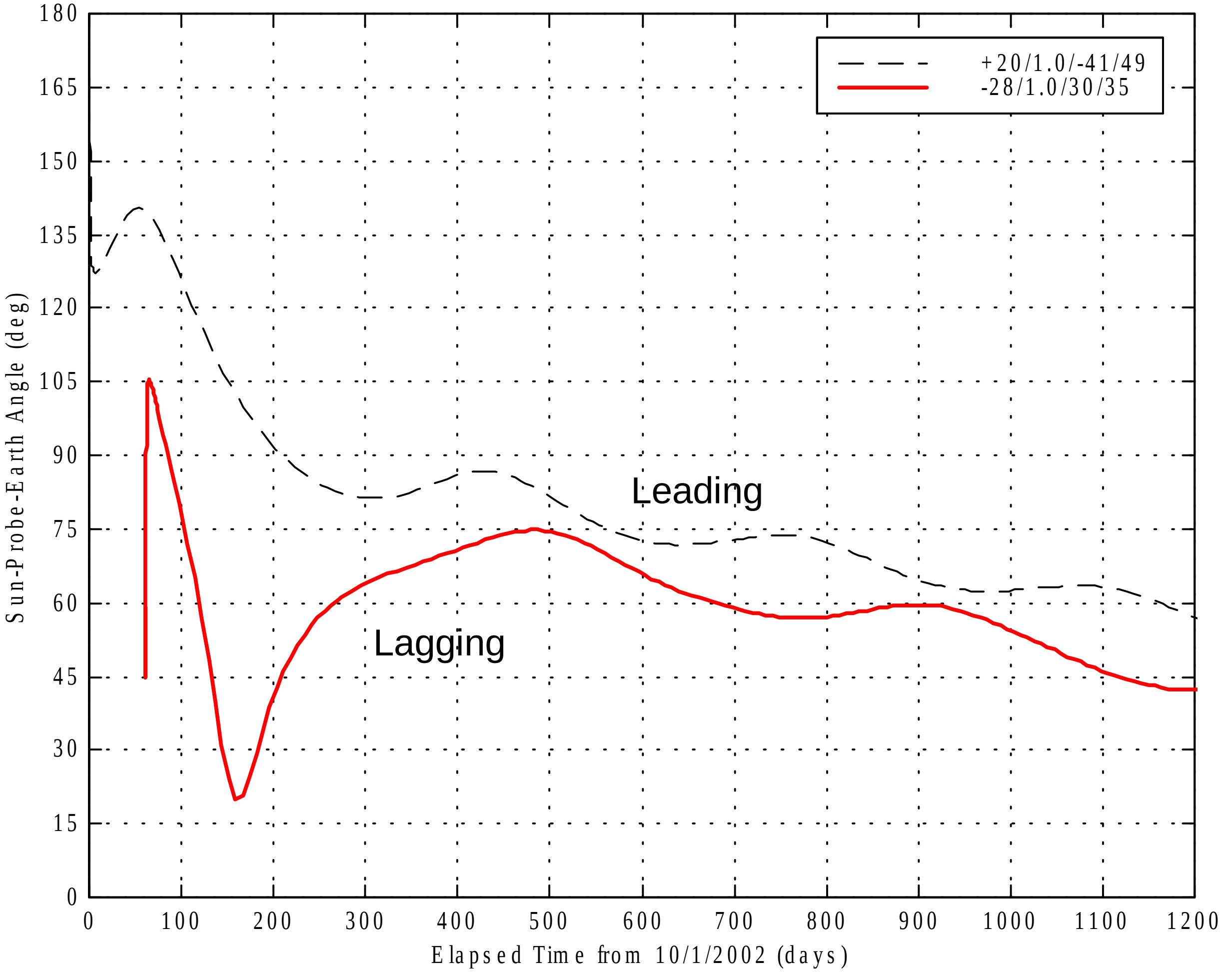
STEREO Orbit Detail
(Geocentric Solar Ecliptic Coordinates)



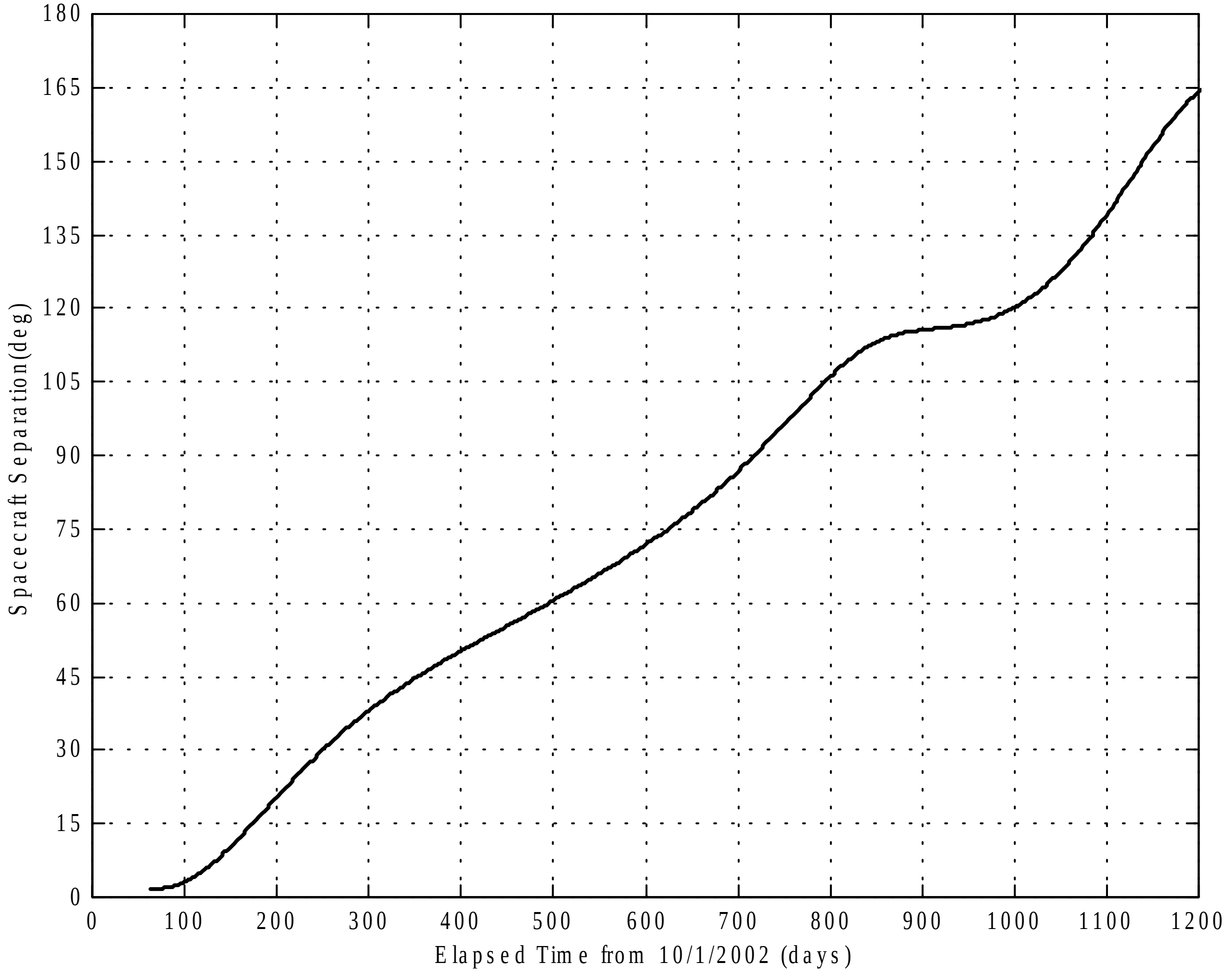
Earth-Sun-Probe Angle



Sun-Probe-Earth Angle



Spacecraft Separation (Alpha angle)



Spacecraft System

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Outline

- Orbits
- Top level and autonomy requirements
- Block diagram
- Sparing philosophy
- Phase A studies
- Technology insertion candidates

Required Orbits

- Leading spacecraft: Lead the Earth at a rate of ~20°/year with a dwell near 20° between 200 and 400 days and one at 45° between 600 and 800 days.
- Lagging spacecraft: Lag the Earth at a rate of ~30°/year with a dwell near 30° between 200 and 400 days and one at 60° between 600 and 800 days.

Spacecraft Requirements

- Conceptually, the instrument suite on each STEREO spacecraft consists of a:
  - Solar Coronal Imaging Package, Radio Burst Tracker, Heliospheric Imager, Solar Wind Plasma Analyzer, Magnetometer, Energetic Particle Detector.
  - In operational mode, instruments operate at 100% duty cycle.
  - The exact instrument compliment will not be known until well into Phase A.
- Solar images are taken simultaneously (±1 sec) from the two spacecraft.
- Support the instrument suite with power, commands, telemetry and unobstructed views for instruments and their radiators.

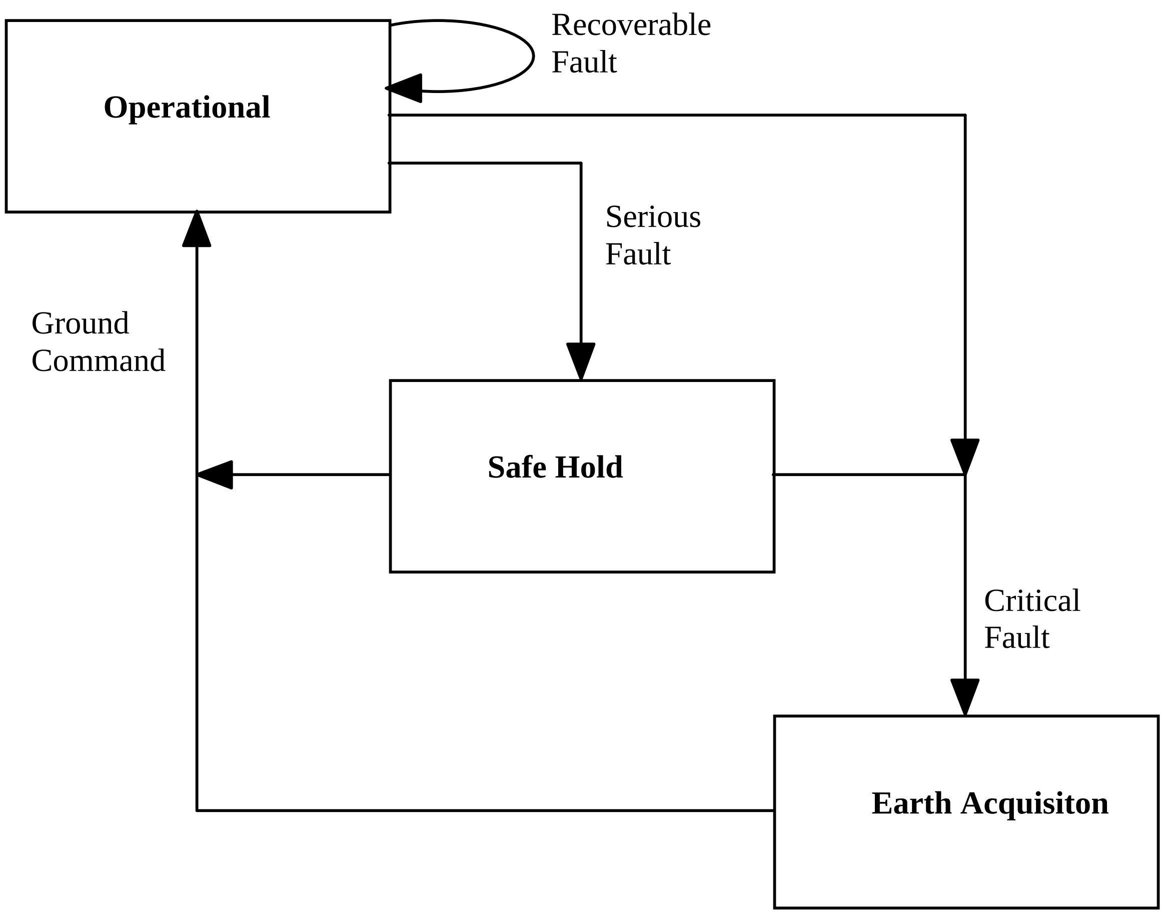
Spacecraft Requirements (Con't)

- The SCIP instrument will provide an error signal to the S/C Attitude Control System. Meet LV interface requirements.
- Spacecraft warns instruments prior to shut off and momentum dump. Instrument survival heaters remain powered.
- Support autonomous LV to operational mode transitioning.
- Maximum time difference of 0.5 seconds between spacecraft.
- Maximum mass 350 kg including 20% margin going into Phase A.
- Maintain full operational mode for Sun/z-axis angle of ±5° or less.

Spacecraft Autonomy Requirements

- The spacecraft will have an autonomous safe-hold mode where the Z-axis is controlled to within 1° of the Sun and the MGA is held within 1° of Earth.
- The spacecraft will have an autonomous Earth-acquisition mode where the Z-axis axis is controlled to within 1° of the Sun and rotation about the Sun line is controlled to 1°/minute ±0.5 min/revolution.
- Provide an autonomous Sun-keep-in capability where the Sun angle is programmable.
- Return to <5° of Sun pointing in <12 minutes from any attitude after any rates have been nulled to zero.
- Capable of autonomously re-positioning the HGA for optimal gain within pre-specified windows. May be overridden or altered from the ground.
- Capable of autonomously momentum dumping within pre-specified windows. May be overridden or altered from the ground.
- Autonomous power management
- Passive thermal control.

Initial Spacecraft State Design



Operational

- Enabled time-tag commands
- All instruments on
- Sun point with all antennas toward Earth
- Telecom over HGA

Safe Hold
(Roll-axis knowledge of assumed)

- Suspend time-tag commands
- Reset spacecraft state (instruments off)
- Sun point with antennas at Earth
- Telecom emergency rates over MGA

Earth Acquisition
(Roll-axis knowledge not assumed)

- Suspend time-tag commands
- Reset spacecraft state (instruments off)
- Sun point and rotate 1 deg per minute
- Telecom emergency rates over MGA
- Recovery initiated with a stop-rotate command

Launch Vehicle

- The baselined launch vehicle for the STEREO mission is the Athena II.

  Launch is separated by two months.
- Each spacecraft will be launched on a separate ELV.
- The shuttle will be studied as an alternative LV. Two spacecraft will be manifested on the same shuttle.
- JHU/APL will make a launch vehicle recommendation at the end of the Pre-Phase A study.

Mission Lifetime

- Designed for a two year mission with expendables designed to last for five years.
    - Mission time starts when both spacecraft are on orbit
- Do nothing to preclude a longer mission beyond two years.
    - Data rate will degrade past the 200 kb/sec at two years requirement
- Two years is the baseline mission duration.

Reliability/Redundancy

- Reliability: Standard JHU/APL reliability practices
- Redundancy: In order to minimize cost, the STEREO spacecraft will be of a single string hardware design based on the TIMED architecture and hardware.
  - Some inherent redundancy exists

Spacecraft Differences

- The two STEREO spacecraft will be form, fit, function and interface identical.
  - Eases build and integration
  - Can take advantage of lessons learned
  - One spacecraft can replace the other in schedule with minimal changes

Radiation

- Spacecraft hardware will be capable of operating for the mission duration in the environment outlined under the reference memo. This includes:

    Component total dose hardness level of 10 Krad.

- All spacecraft electronics will be latch-up immune and SEU tolerant.

Reference: GSFC (Janet Barth) radiation environment analysis and Memo SOR-98048.

Cleanliness

- Handling and I&T Environment

  Class 100,000 during bus integration.
- Instrument selection may dictate the use of more stringent cleanliness requirements
- A Contamination Control Plan will be written after instrument selection and requirements have been defined.

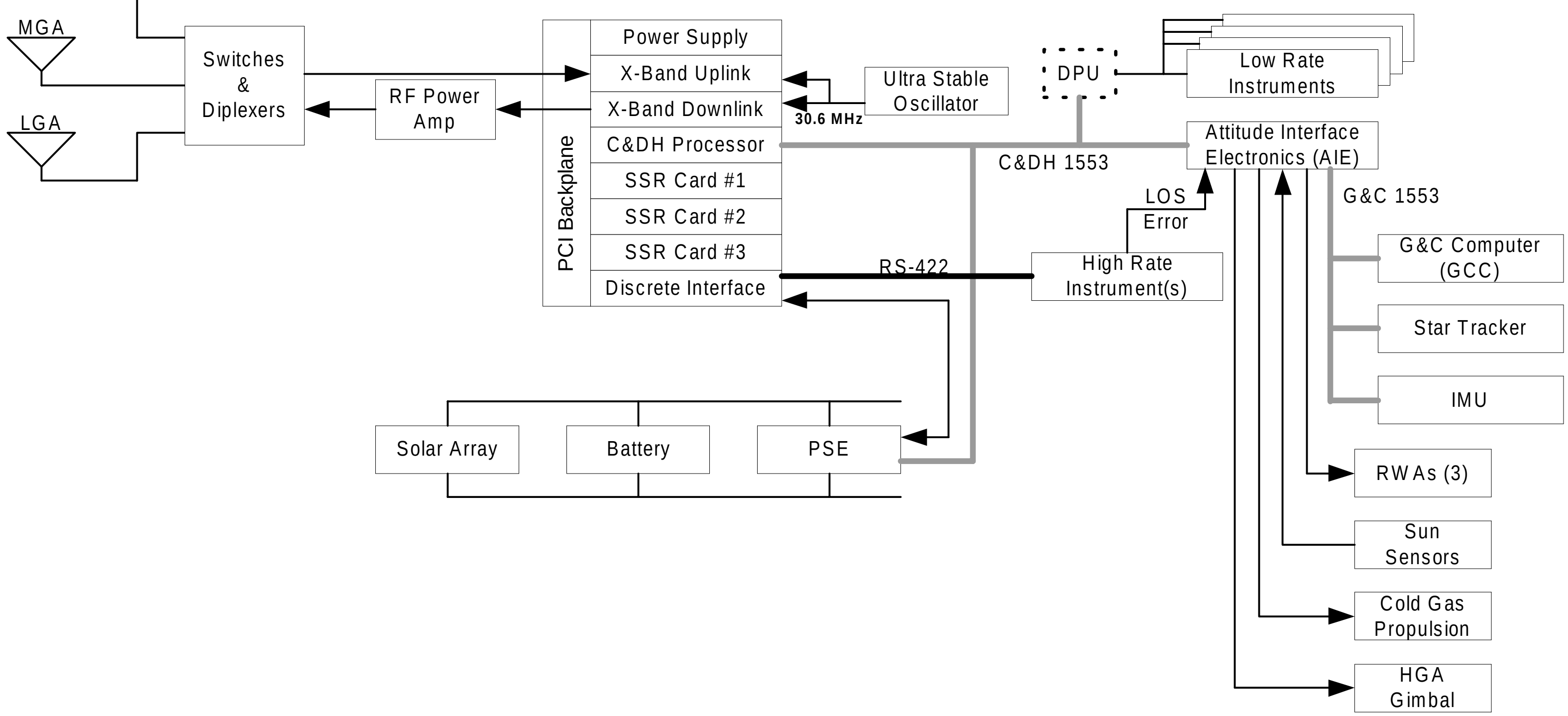
Communications

- Science data volume requirement is 5 Gbit/day.
- Nominally, complete volume will be transmitted to the Earth within 24 hours

  Data rates will vary with Earth probe distance.
- Maximum DSN pass time is 8-hours (at end of mission).
- Each STEREO spacecraft will support a low rate “broadcast mode” of 500 b/s which will be transmitted at all times, when not transmitting high rate data.

STEREO Block Diagram

The DPU is currently under evaluation. A non-DPU implementation would require all low rate science instruments to transfer data via the 1553 bus.



Flight Spares Philosophy

- Sparing will occur only at the piece part level. There will be no one for one box level or procured hardware spares (except for battery).
- A spare flight board will be fabricated/purchased for all in house boards (except for the SSR). These boards will be left unpopulated. One set of components will be purchased for every two used.
- The goal is to minimize cost without undue schedule risk.
- Additional sparing will be considered on a case by case basis.

Current Requirements Deficiencies

- Transmission gap between day 76 and 125 on the leading spacecraft.
- Minimum data rate at the end of two year mission 0.97 AU (Data rate is 82 kb/s). Day 661 drops below 200 kb/s (34m HEF).
- Jitter requirement–Additional analysis during Phase A required.

Phase A Studies

- G&C/Safing architecture trade

  Removal of AIU processor, RTX-2010 compiler is no longer supported.
- MiniMOCS
- Non rotisserie Safe Mode

  Using low gain antenna in safe mode in conjunction with 70 m DSN.
- Continue Jitter Analysis
- Communications gap

Technology Insertion Candidates

- Momentum dumping via trimmable flaps
- Non-coherent navigation (baselined)
- LiIon battery
- Advanced recorder management
    - File system

Command and Data Handling

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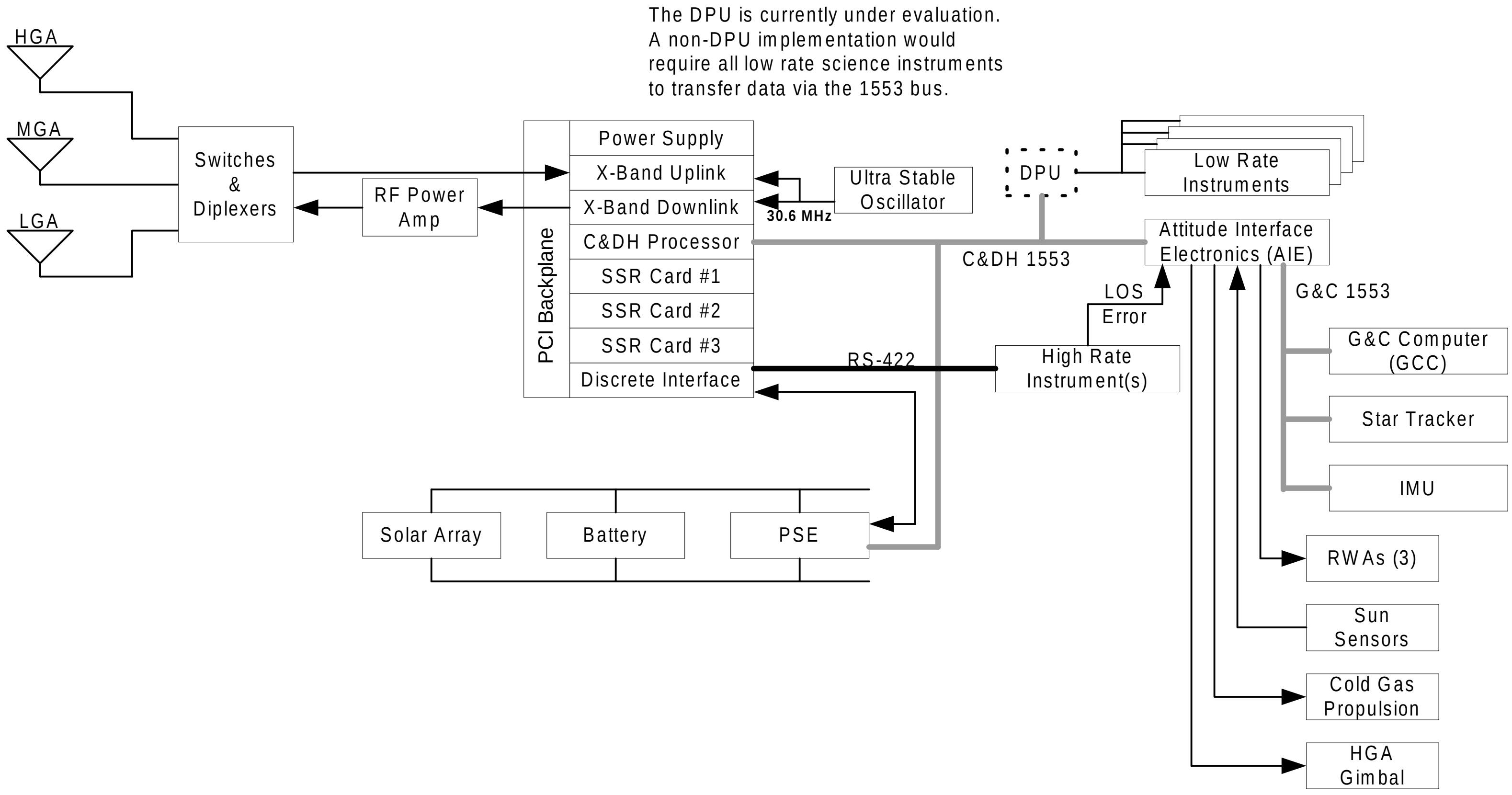
Spacecraft Block Diagram



C&DH System Requirements

- Implementation requirement
  - Re-use TIMED architecture
- Functional requirements
  - Uplink command and stored command management
    - CCSDS compatible uplink
    - Provide for two data rates: 100 bits/sec and 7 bits/sec
  - Telemetry data processing
    - CCSDS compatible downlink
    - Provide for maximum data rate of 800 Kbits/sec (allows for transmission of 8 Gbits/3 hr DSN downlink time)

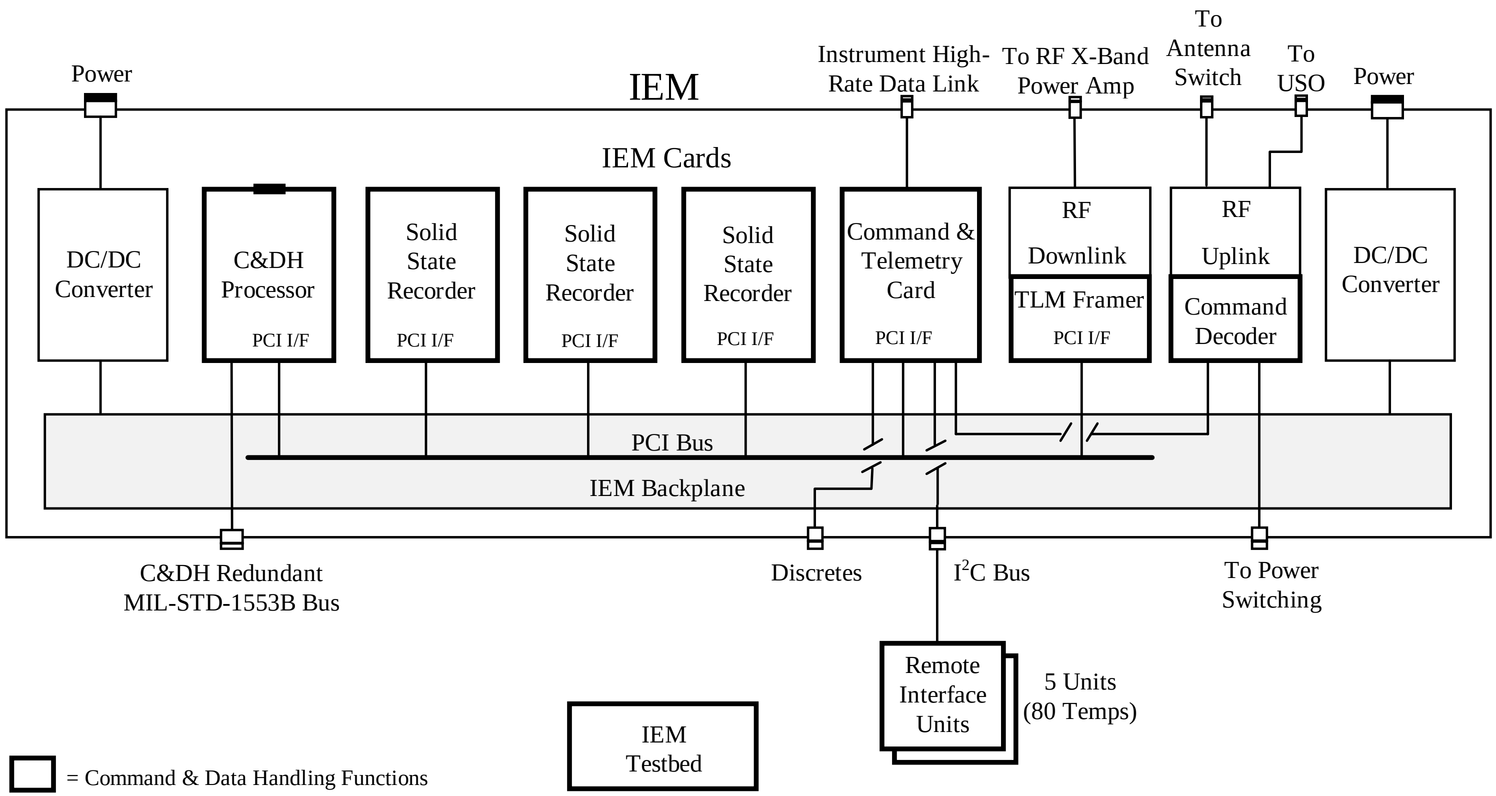
C&DH System Requirements (con't)

- Functional requirements
  - Mass storage of science and engineering data
    - 5 Gbit science volume + housekeeping + overhead and margin
    - Simultaneous and random read/write capability
    - Error management and graceful degradation
    - Interleave real-time data with recorder playback data, but optimized for science (e.g., 97% science data, 3% real-time products)
  - Support science data collection
    - Provide real-time downlink mode for instruments (one at a time)
    - Provide variable telemetry bandwidth allocation for instrument data, selectable by the science team
    - Provide "Broadcast Mode" data collection and transmission at 500 bits/sec when not transmitting high rate data
    - Support instrument combined maximum data generation rate (~410 Kbits/sec) for storage and real-time downlink

C&DH System Requirements (con't)

- Functional requirements (con't.)
  - Support engineering data collection
    - S/C temperatures, voltages currents and telltales
    - Non-coherent navigation data
    - Instrument status information
  - UT maintenance and distribution
    - 0.1 second accuracy
  - Autonomous fault protection
  - Manage subsystem intercommunication
    - C&DH MIL-STD-1553B bus controller

Integrated Electronics Module (IEM) Configuration Baseline



TIMED: Processor and SSR Requirements and Capabilities

TIMED	REQUIREMENTS	CAPABILITIES
C&DH Processor	32-Bit architecture 2MBytes SRAM 4MBytes EEPROM MIL-STD-1553B redundant bus PCI local bus	Mongoose V CPU clocked at 12 MHz 9.6 RISC MIPS throughput
Solid-State Recorder	1.9 Gbit Capacity 4Mb/s Pk Read Rate 30Kb/s Pk Write Rate Random read/write capability Map around bad memory blocks Error management Simultaneous read/write	2.5Gbits Capacity 8Mb/s Pk Read Rate, 8Mb/s Pk Write Rate Simultaneous R/W, 8Mb/s combined rate Random access at code block level Settable, auto-incrementing R/W pointers Error management: Reed Solomon encoding with correction of up to 5 bytes with errors per block (245 bytes/block). Probability of >5 bytes in error per block is: $<10^{-21}$, 24-hour scrub rate $<10^{-25}$, 4-hour scrub rate memory error rate: $<10^{-12}$ err/bit/sec

STEREO: Processor and SSR Requirements and Capabilities

STEREO	REQUIREMENTS	CAPABILITIES
C&DH Processor	Same as TIMED	Same as TIMED
Solid-State Recorder	5 Gbit + housekeeping + OH + Margin 750Kb/s Pk read rate 450Kb/s Pk write rate Random read/write capability Map around bad memory Error management: Max error rate $<10^{-9}$ bit errors/3-days	7.5Gbits capacity 8Mb/s Pk read rate, 8Mb/s Pk write rate Simultaneous R/W, 8Mb/s combined rate Random access at code block level Settable, auto-incrementing R/W pointers Error management: Reed Solomon encoding with correction of up to 5 bytes with errors per block (245 bytes/block). Probability of >5 Bytes in error per block is: $<10^{-TBD}$ w/scrub rate of every TBD-hrs memory error rate: $<10^{-TBD}$ err/bit/sec

Other IEM Internal Subsystem Functional Requirements

Command & Telemetry Card	Route uplink commands from the command decoder to the C&DH processor and C&DH processor relay commands to the command decoder Collect S/C temperature data and IEM temp and voltage telemetry data Provide interface for high rate instrument science data (RS-422)
Downlink Framer	Builds CCSDS compatible realtime, recorder, and null telemetry frames from data collected from the C&DH processor and the SSR and produces a serial data stream to the RF modulator. Timing chain and counter to provide 1 Hz time marking and MET, respectively (clocked by S/C ultra-stable oscillator)
Uplink Command Decoder	Receive CCSDS compatible commands from the Uplink Receiver command detector (or from the GSE). Route all commands to the C&DH processor, via the C&T subsystem. Route all relay commands, either uplinked or generated by the C&DH processor, to the power switching subsystem. Perform autonomous load reduction upon receipt of a low bus voltage indication from the power subsystem (execute a stored set of relay commands).

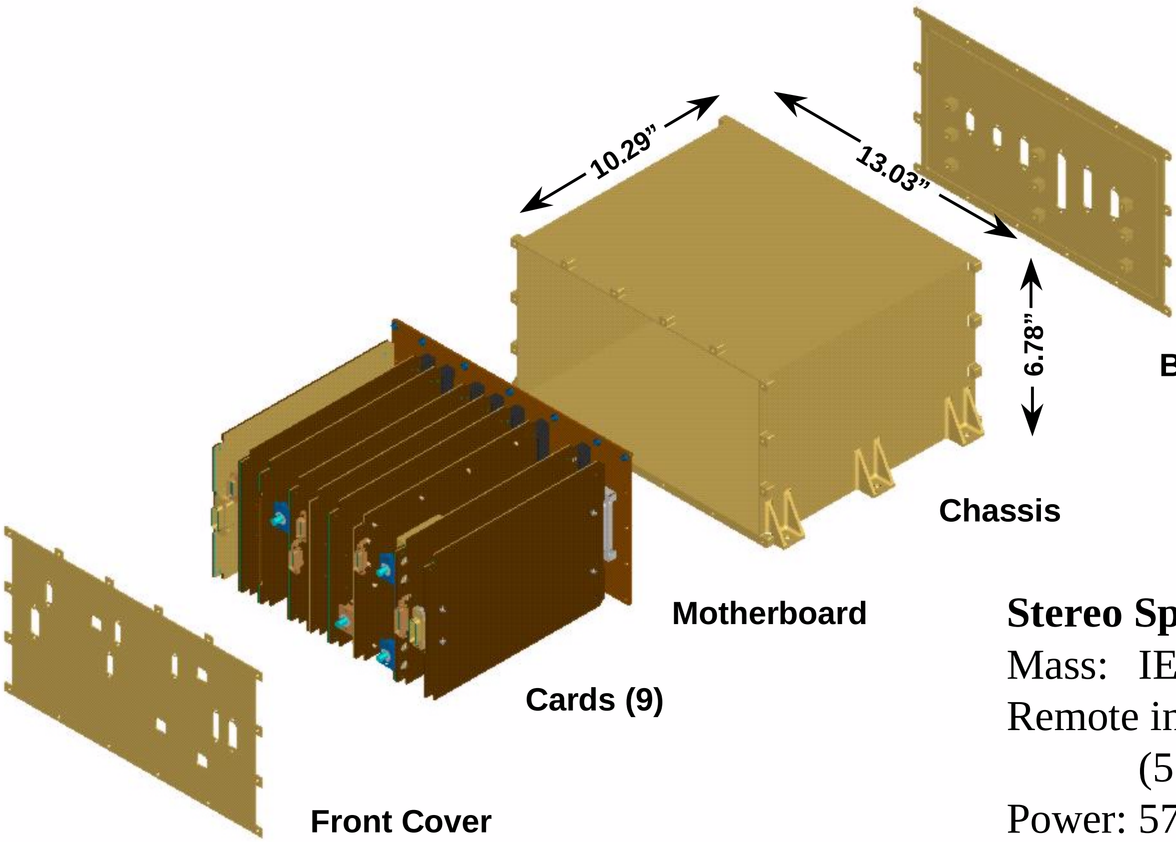
Candidate Studies

- Solid-State Recorder–Make versus Buy
  - "Buy" considerations:

    Acquire a unit that can be either interfaced to or inserted into the IEM.
  - "Make" considerations:

    Modified baseline–Upgrade the SSR using denser memory technology and/or packaging reducing it to a single card but with a 10 Gbit capacity.
- Temperature Remote I/O (TRIO) Chip–Technology Insertion
  - Compatible with existing IEM I^2C bus system
  - Part packaging and qualification needs to be completed. Same part sought by JPL for use in X2000 program.

TIMED IEM Chassis



Stereo Specifications

Mass: IEM: 10.5 Kg

Remote interface unit (RIU): 1.2 Kg (5 units)

Power: 57 W ave., 62 W peak (9-cards, 5 RIUs)

Guidance and Control

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G&C Requirements–Design Drivers

- Spacecraft pointing–(3 σ)

	Roll	Pitch/Yaw
– Knowledge:	± 20 arcsec	± 0.1 arcsec
– Control:	± 0.1°	± 20 arcsec
– Jitter:	30 arcsec RMS	1.5 arcsec (0.1 to TBD Hz)

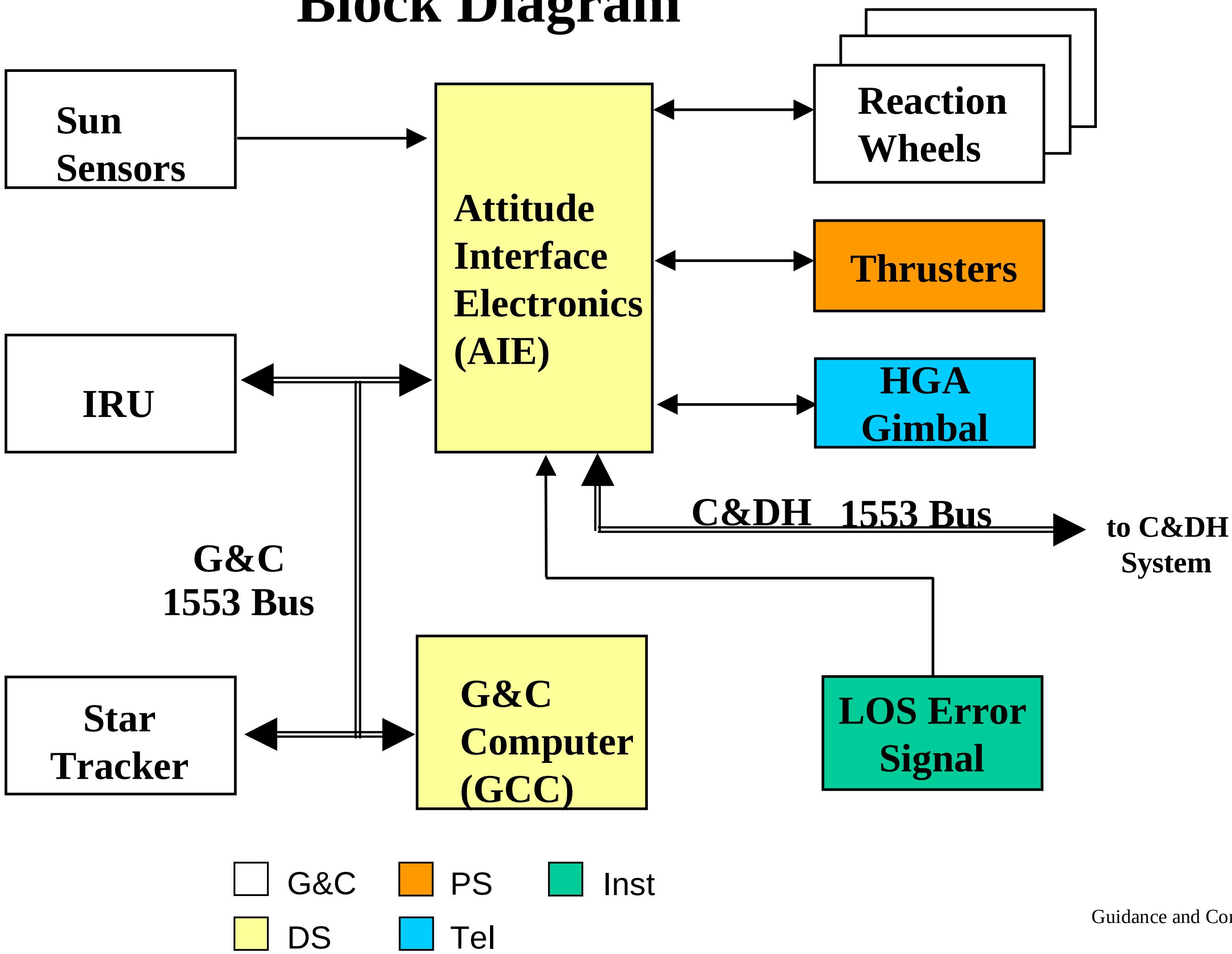
  (with SCIP error signal, which is ± 0.1 arcsec)
- Jitter is challenge
- Need high control bandwidth =>
  - High wheel torque
  - Fast sampling rate
  - Minimize disturbances
  - Modern control techniques

G&C Requirements–Other

- Point LOS within 5 arcmin of Sun for SCIP acquisition
  - Requires good coalignment
- Nominal HGA pointing to 0.1°; maintain HGA pointing during thrusting; complete autonomous thruster firings within 300 seconds
  - Sets gimbal step frequency
  - Need small impulse bit and small Δt
  - In-flight HGA alignment cal – TBD
  - On-board ephemeris for HGA pointing vectors
- Momentum storage capacity > 4 days in operational mode
  - Sizes wheel momentum
- Return from any attitude in < 12 minutes
  - Thruster attitude control – TBD
  - May size wheel torque
- Solar pressure momentum bias within Sun-angle limit

STEREO Guidance & Control System

Block Diagram



Baseline G&C Equipment

Item	Heritage	Performance
IMU	NEAR	HRG, 0.01°/hr½
Star tracker	TIMED	3 arcsec, 7.5 Mv stars
Reaction Wheels	NEAR	Torque: 0.025 Nm Momentum: 4 Nms
Sun Sensors	NEAR	0.5° quantization 0.25° accuracy
AIE	TIMED	
G&C Computer	TIMED	

Inertial Reference Unit (IRU)

- Supplier: Delco Electronics
- Gyros:
  - Delco 130Y Hemispherical Resonator Gyros (HRG)
  - Rate bias stability < 0.001°/hr, over 16 hr
  - ARW < 0.01°/hr$^{1/2}$
- Redundancy:
  - NEAR: redundant CPU, power; four gyros
  - Cassini: single-string
- Projected P_S (system function) = 0.9996 for mission life
  - (four gyro IRU)

Reaction Wheel Assembly (RWA)

- Supplier: Ithaco, Inc. (Type A)
- Characteristics:
  - Brushless DC motor
  - Bipolar tachometer
  - Separate electronics, stacked to save weight and space
- Performance:

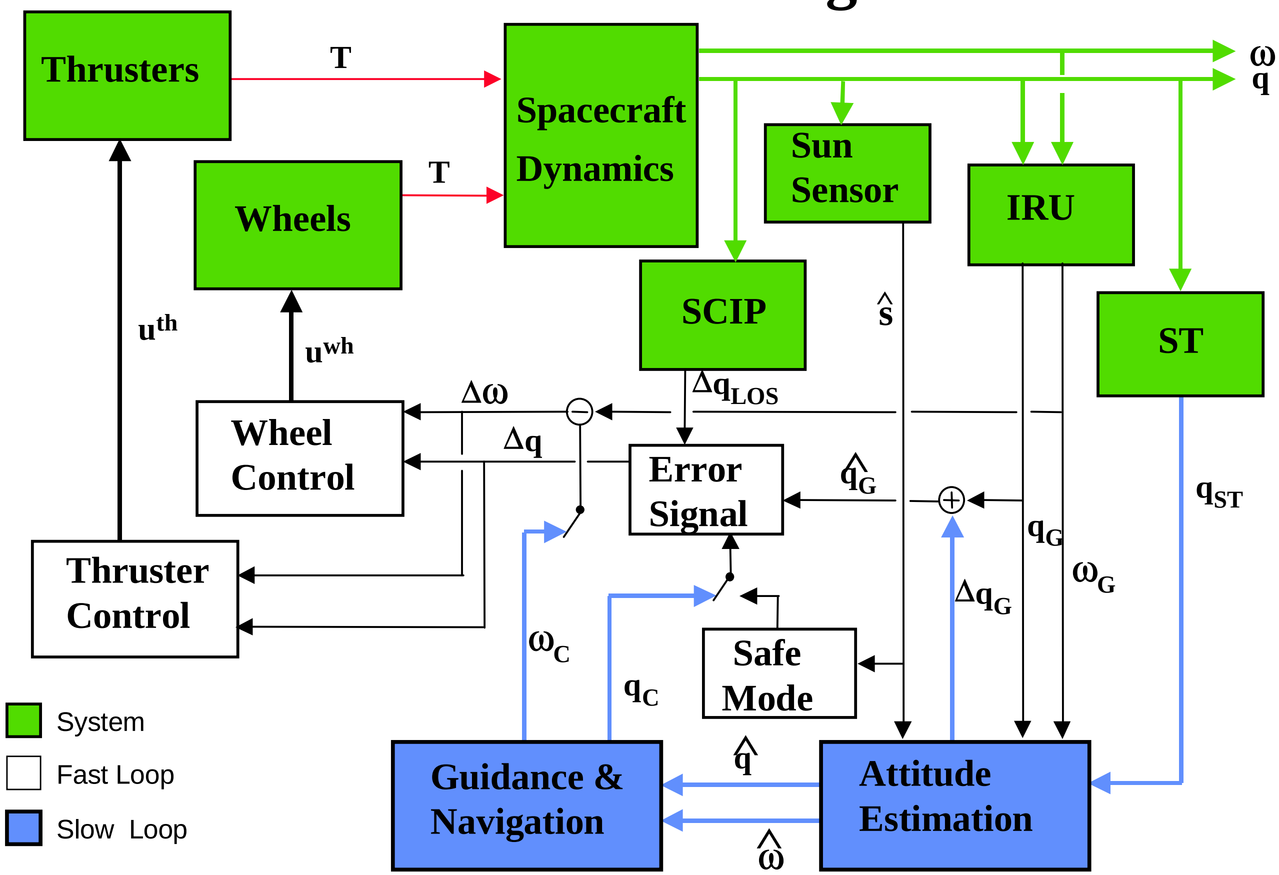
– Angular Momentum:	4 Nms (@ 5100 RPM)
– Torque:	0.025 Nm *(higher torque possible)*
– Unbalance:	
static	< 1.5 gm cm
dynamic	< 40 gm cm^2
– Torque noise PSD:	1×10^{-11} $(Nm)^2$/Hz, 0.1 to 1 Hz
– Continuous operating life:	> 4 years

Sun Sensors

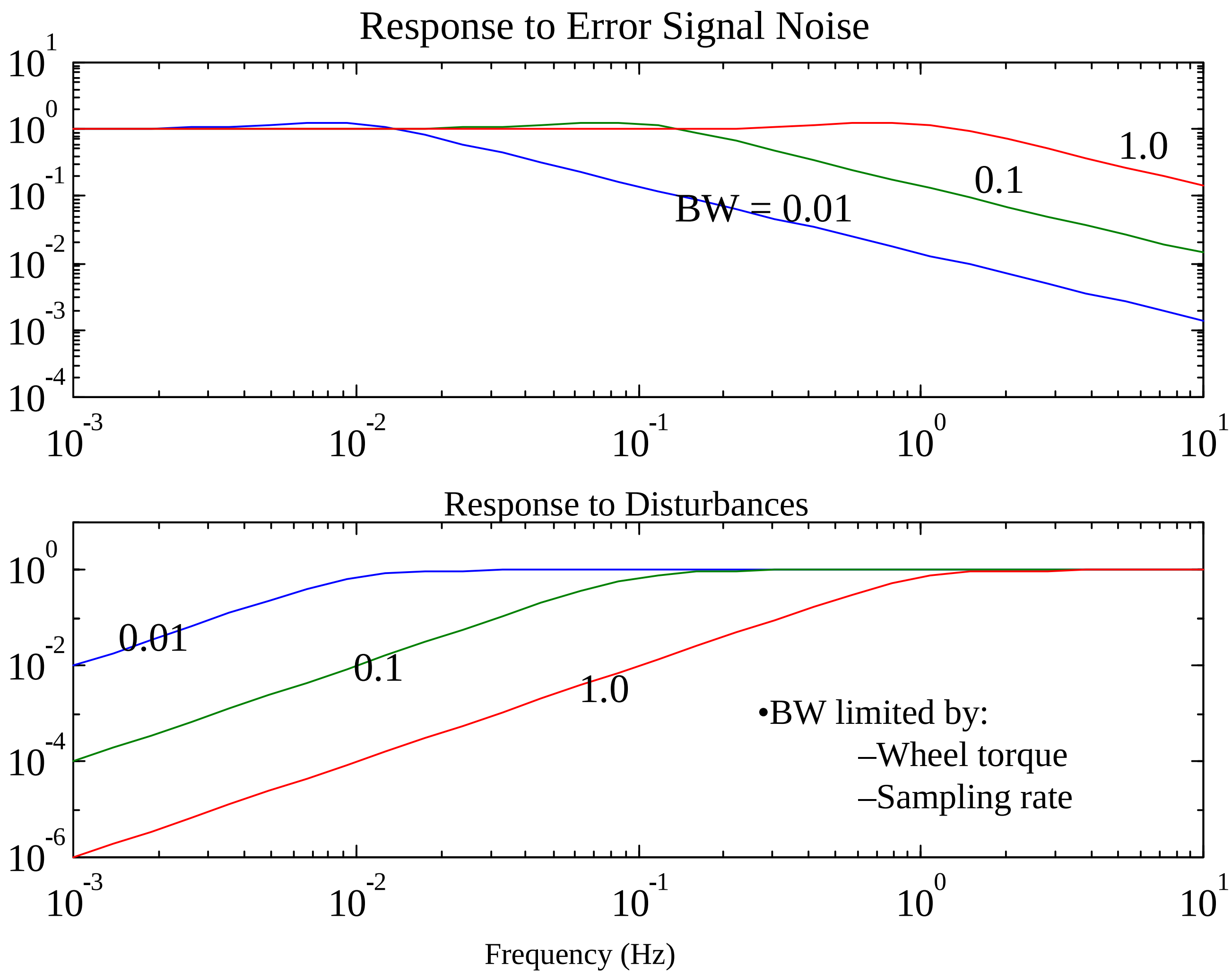
- Supplier: Adcole
- Digital Solar Attitude Detector (DSAD) system
  - Five detector heads, each measures 2-axis Sun vector in ±64° FOV
- Accuracy:
  - 0.5° quantization
  - 0.25° bit transition-angle accuracy
- Flight proven, many times

Guidance & Control

Functional Block Diagram



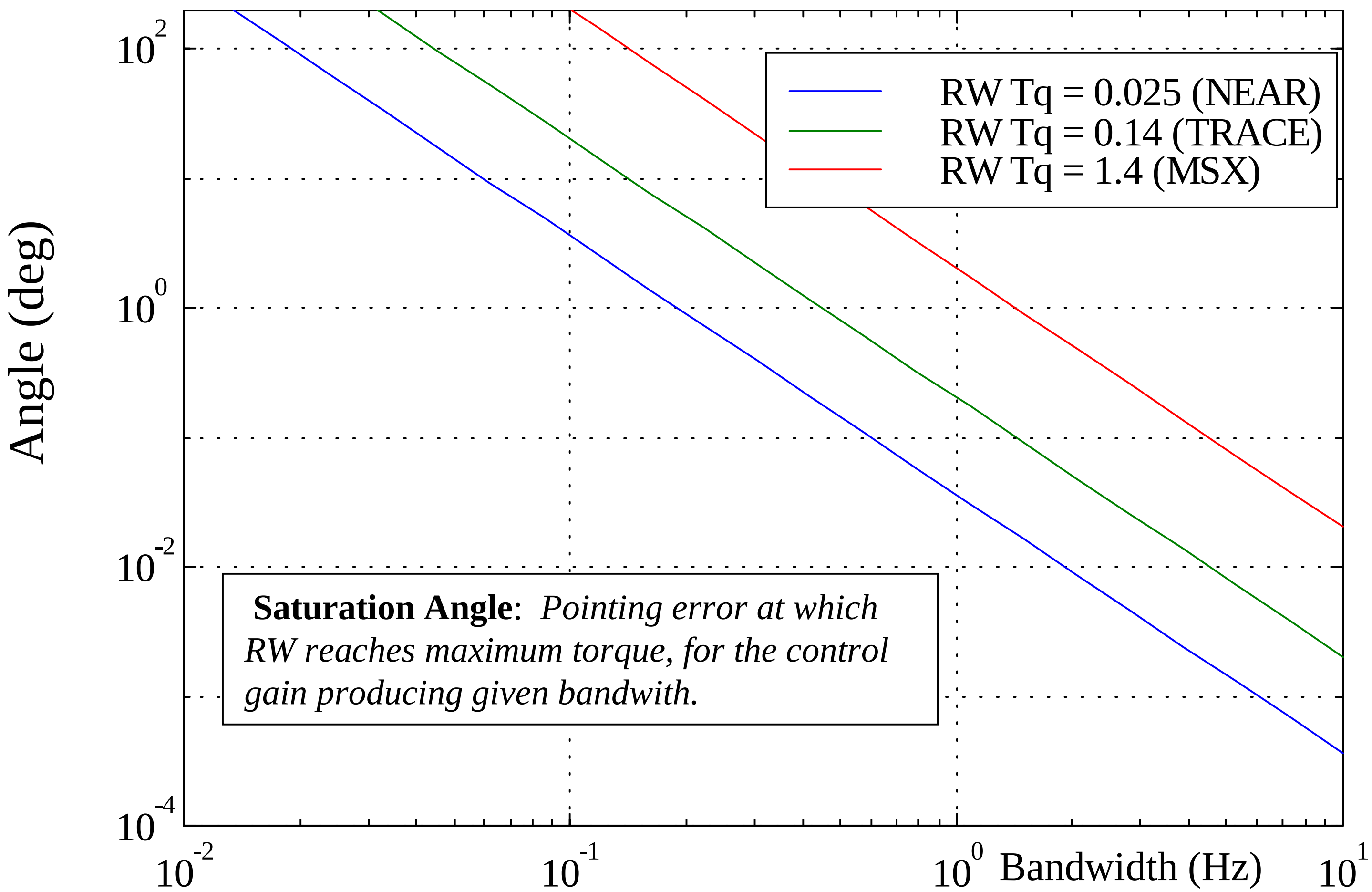
Control Bandwidth (BW) Effects)



Star Tracker

- Supplier: Lockheed Martin
- Accuracy:
  - 3 arcsec P/Y; 32 arcsec R (1σ)
  - 7.5 Mv stars
  - 8.8° square FOV
- Quaternion output
  - Autonomous star ID within ~2 sec
  - 5 Hz update, 1553 interface
- Flown on DS1, P59; to fly on TIMED, EO1, MAP, IMAGE, ...

RW Saturation Angle (deg) vs. Control Bandwidth



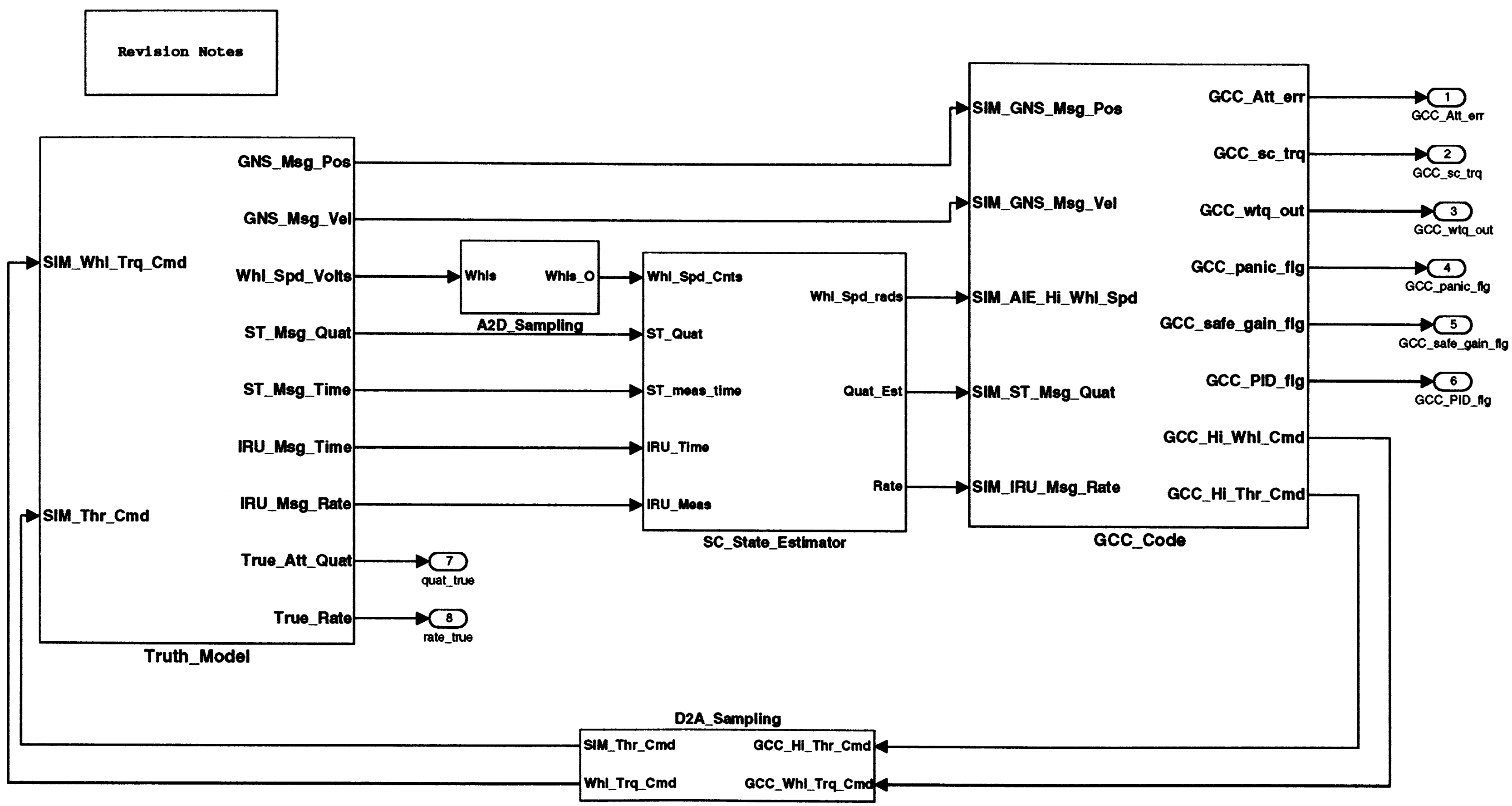
Redundancy Considerations

- Four Wheels
  - Full capability if any one fails
  - Enable wheel speed control to avoid troublesome frequencies
- Four Gyros
  - Full capability if any one fails
  - Lower noise if all four used
- Fine Sun Sensor
  - In addition to, or in place of, coarse DSADs
  - Enable mission pointing without LOS error signal
- ST gives some backup to LOS error signal

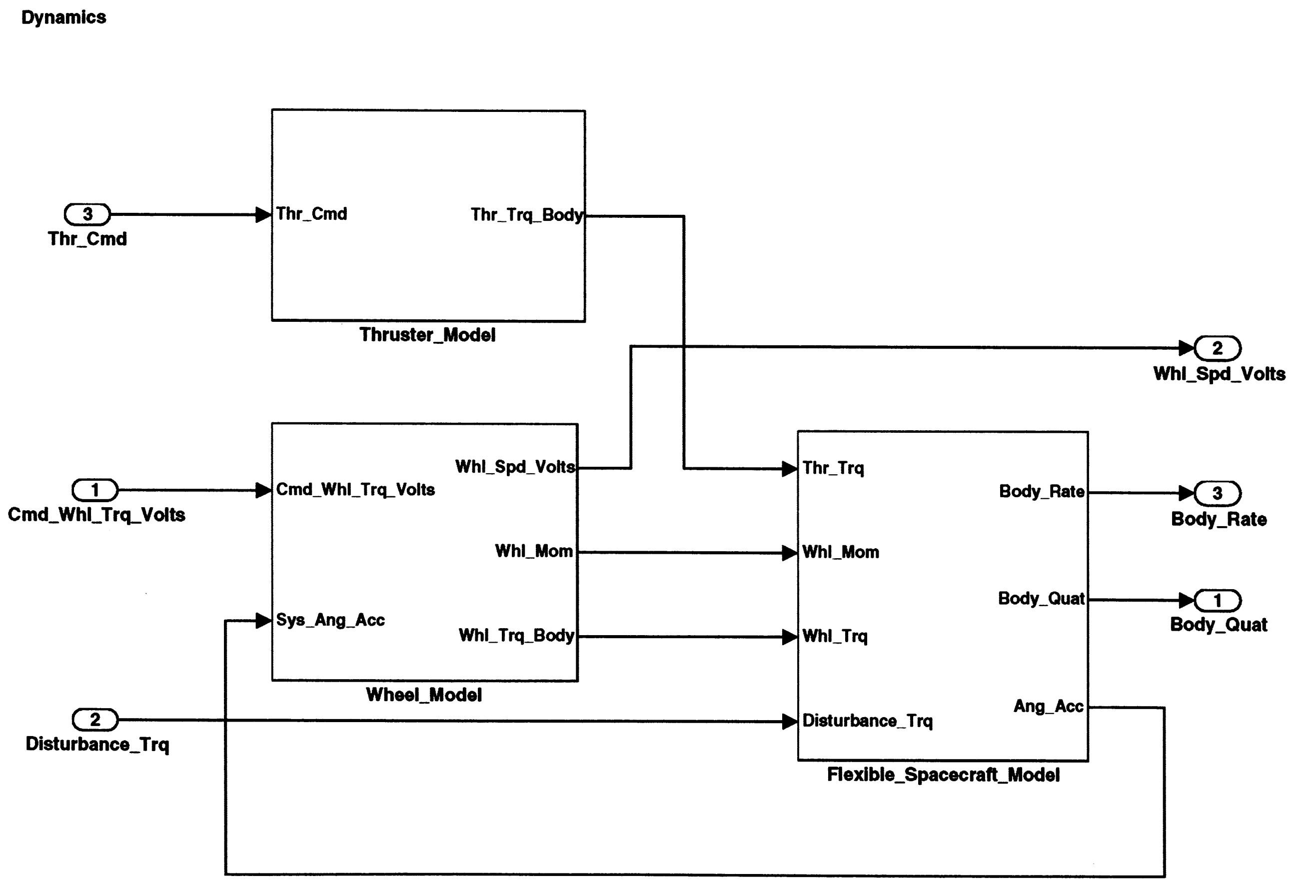
Momentum Bias Mode

- Possible for safe mode, or if y or z wheel fails–
  - x wheel runs at large fraction of its max speed
  - Other wheel(s) used to damp nutation
  - Precession by thruster firings
- Degraded pointing accuracy –
  - Stability dominated by nutation
  - Accuracy limited by momentum precession
- Fuel for angular momentum precession:
  - About 150 mgm/day for 1°/day precession (H=4 Nms, Isp=65 s)
- If x wheel fails –
  - y and z RW control still possible
  - Two-sided thruster limit cycle for x

Top Level STEREO



Preliminary STEREO Dynamics



Flexible Spacecraft Dynamics

$$I\ddot{\theta} + M_I\ddot{\xi} = N - \dot{h} - \dot{\theta}\times(I\dot{\theta} + h + M_I\dot{\xi})$$
$$\ddot{\xi} + D\dot{\xi} + \Lambda\xi + M_I^T\ddot{\theta} = 0$$

where ξ **-- modal coordinates of flexible structures;**

M_I **-- interaction matrix between flexible structures and rigid spacecraft body**

$M_I\dot{\xi}$ **-- total momentum from flexible structures;**

$M_I\ddot{\xi}$ **-- total acceleration from flexible structures;**

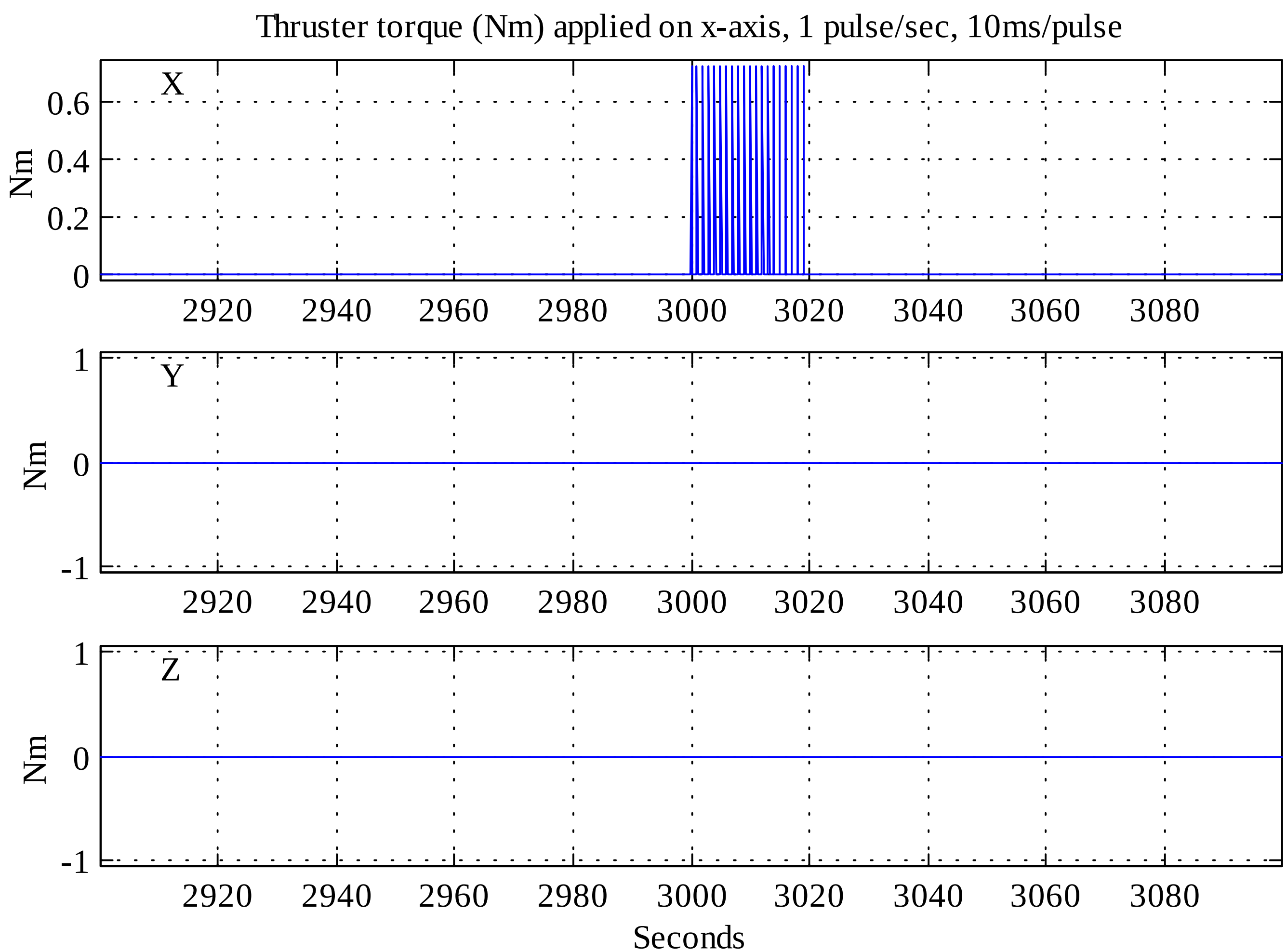
$D = 2k\cdot diag\{\omega_{f1},...,\omega_{fN}\}$ **-- natural damping matrix of flexible structure;**

$\Lambda = diag\{\omega_{f1}^2,...,\omega_{fN}^2\}$ **-- stiffness matrix of flexible structure.**

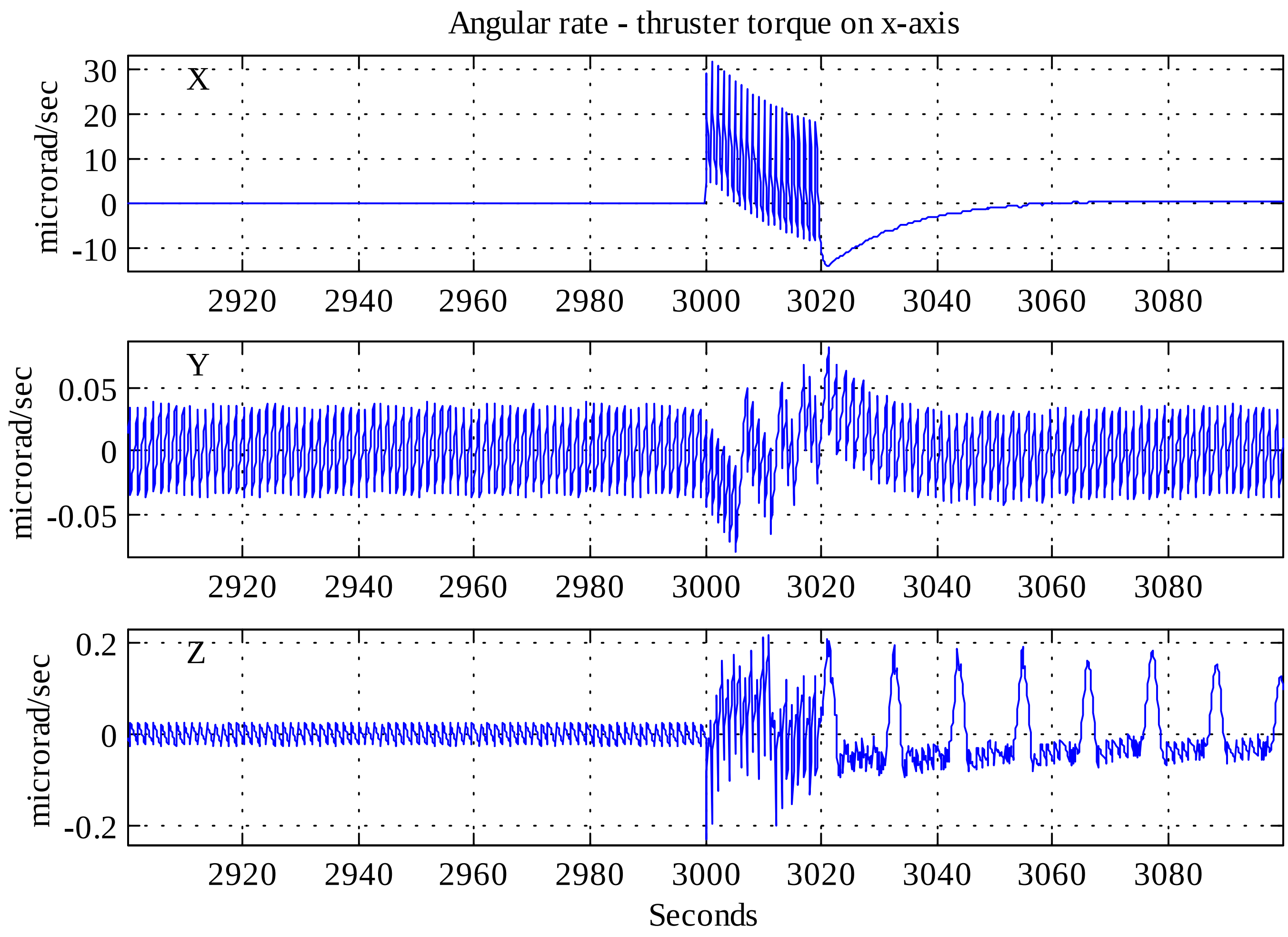
Assumptions:

- **Uniformly distributed beam like structure**
- **Normalized modal model, with lowest frequency** $f_0 = \frac{1}{2\pi}\sqrt{\frac{3EI}{(M+0.243\rho l)l^3}}Hz$ **, and**
  $f_i = i\cdot f_0, i = 1,2,...N$ **, based on preliminary structure parameters.**
- **Simplified interaction matrix, based on preliminary geometry of flexible structures**
- **Uncoupled flexible structure models**
- **No external force on flexible structures**

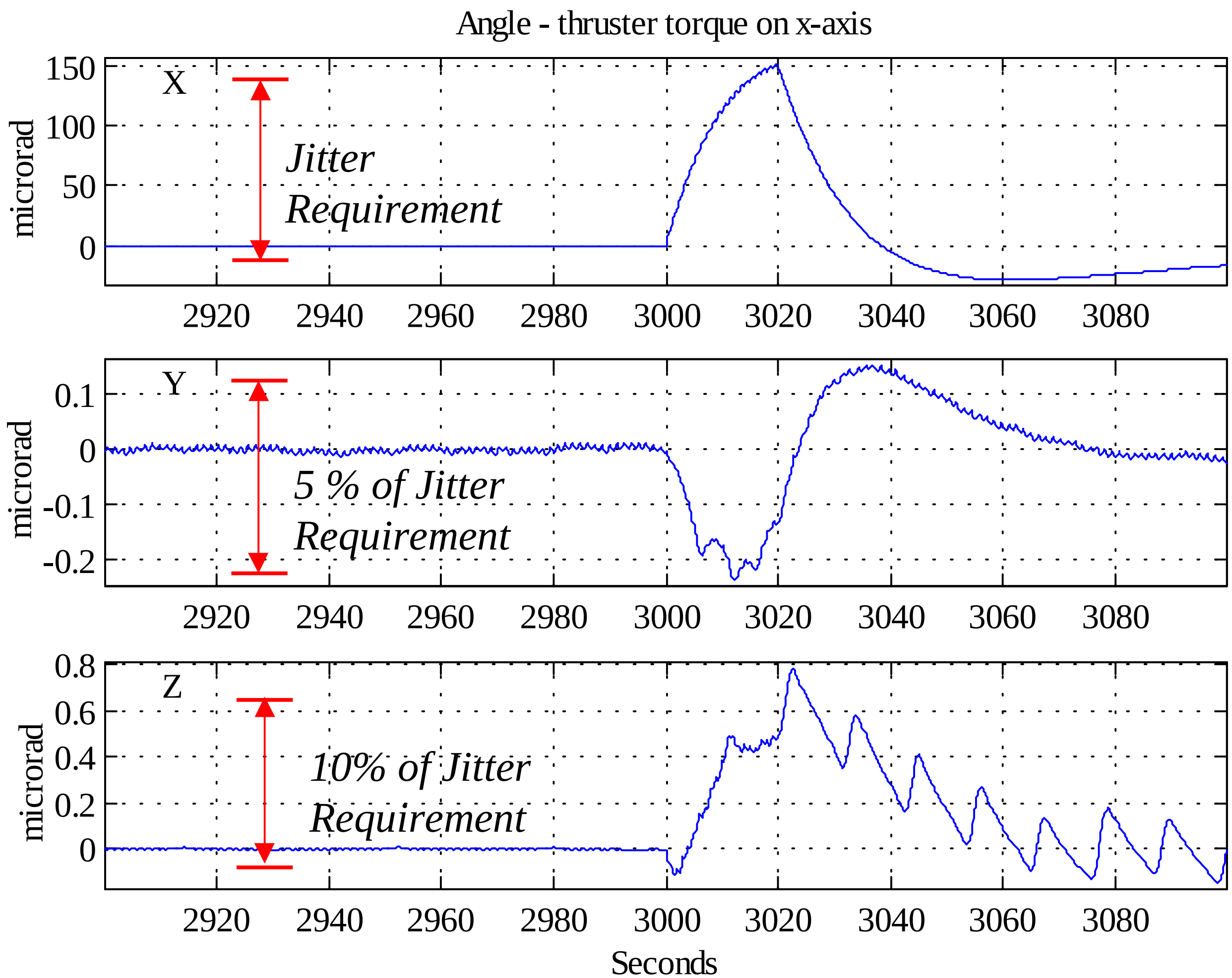
Thruster Torque, Flexible Simulation



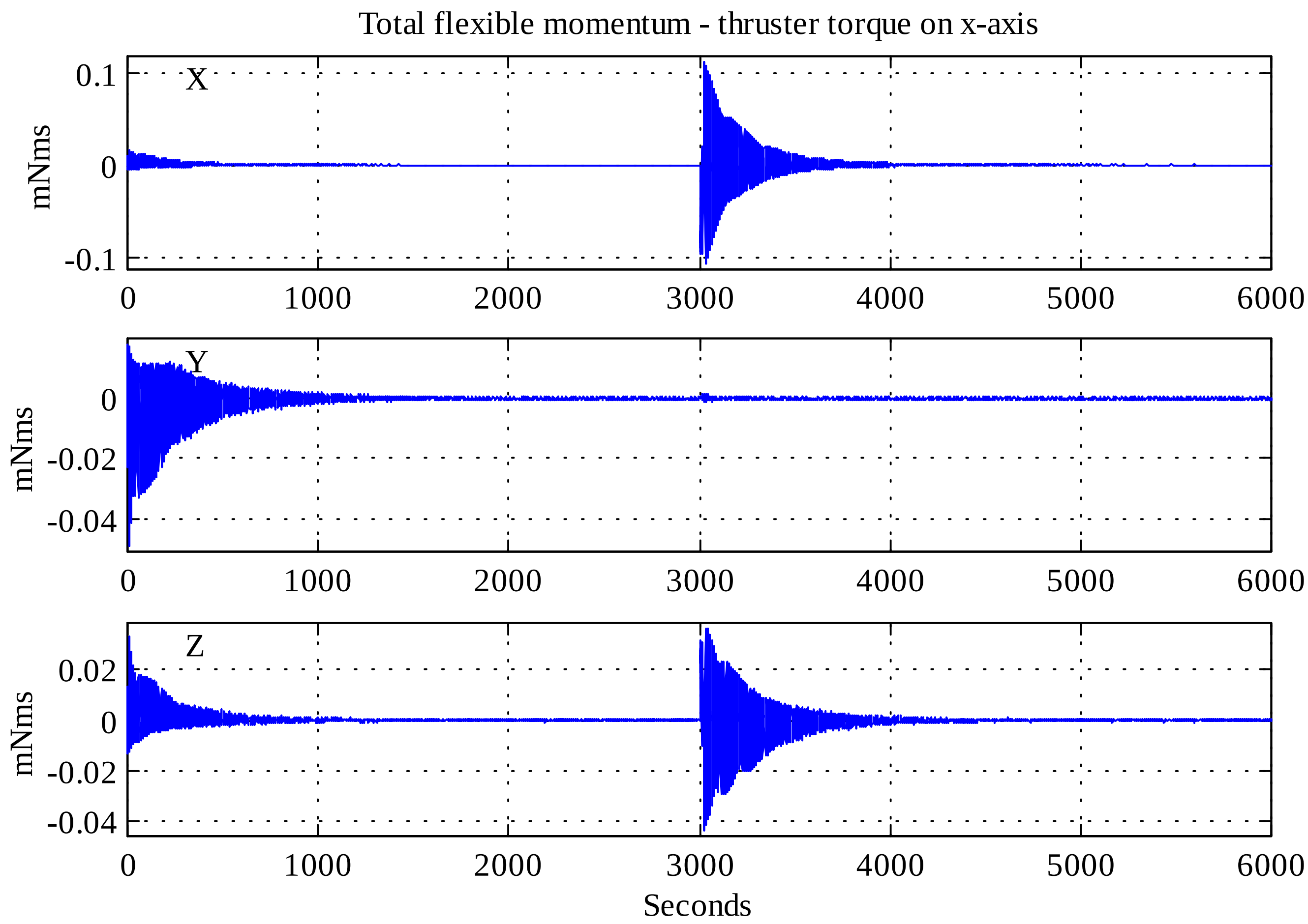
Angular Rate, Flexible Simulation



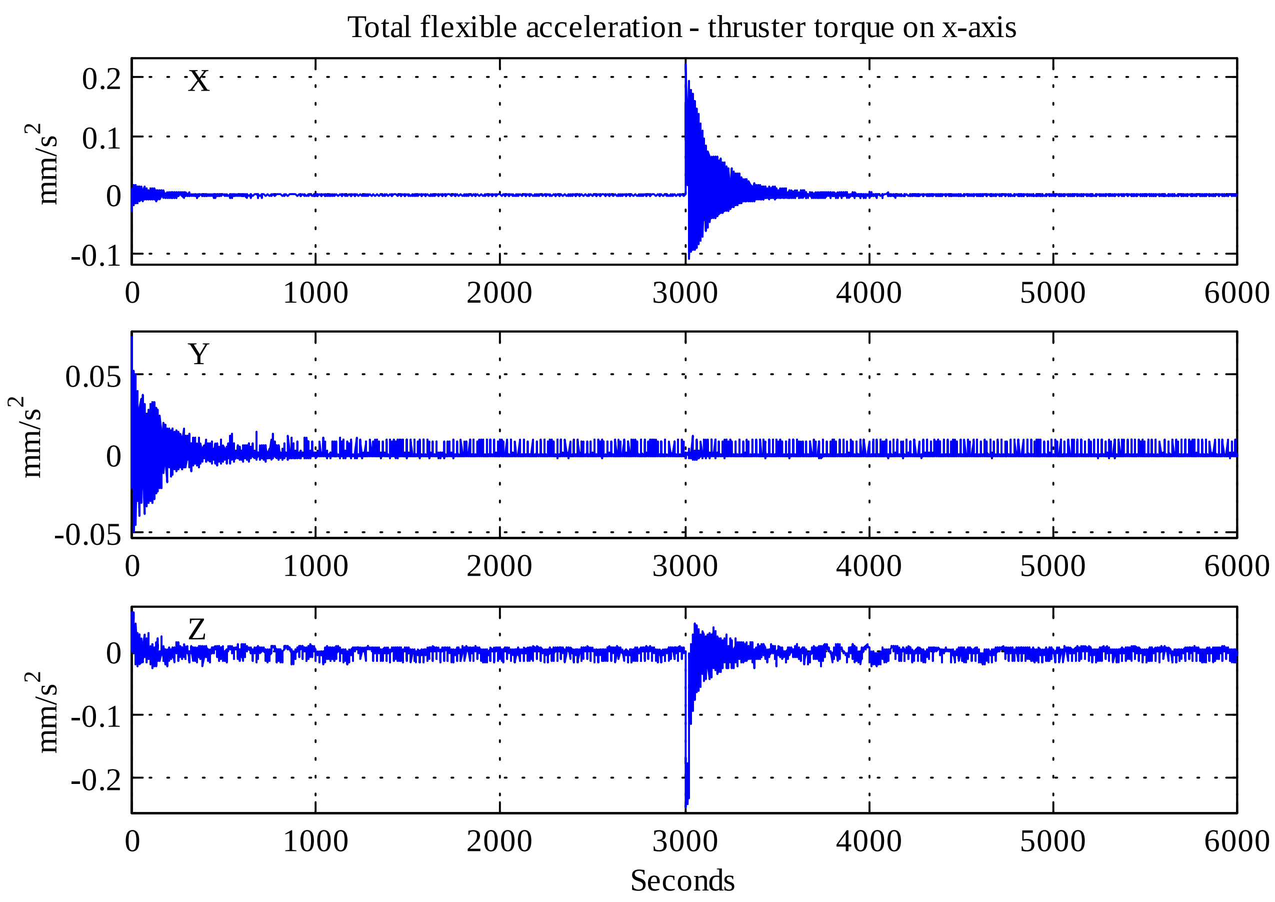
Pointing Error, Flexible Simulation



Angular Momentum in Flexible Modes



Linear Acceleration, Flexible Modes



Software

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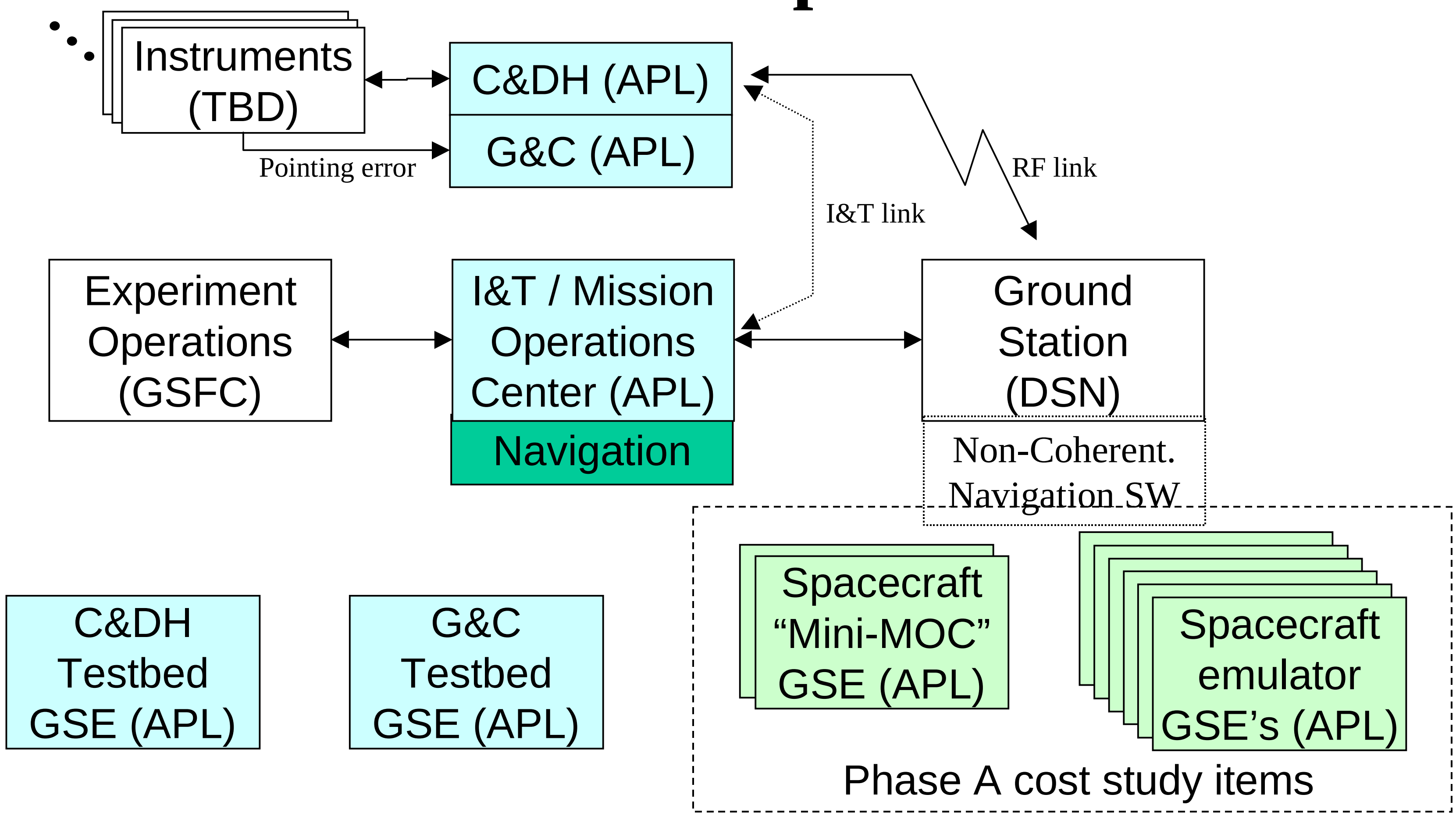
Software Components



C&DH S/W Requirements

- Support CCSDS-compatible uplink/downlink
- Perform power management
- Perform spacecraft health and status monitoring
- Maintain and distribute time to 0.1 sec accuracy
- Allow for software upgrade capability
- Distribute commands to subsystems
- Support 7.5 Gbit recorder w/simultaneous record, playback
  - Dump entire recorder in 8-hours at 200 kbits/sec., or...
  - Dump recorder at max. downlink rate of 800 kbits/sec...
  - While continuing to record new data from science instruments at their maximum rates

C&DH S/W Requirements (con't)

- Support science instruments
  - Provide "transparent" forwarding for instrument commands, telemetry
  - Provide limited space for instrument stored commands (~200 kbytes)
  - Label science and attitude history packets so they can be identified and routed to GSFC without inspection
  - Collect max rates (~450 kbps total) from all instruments simultaneously
  - Support "real-time" commanding and science downlink during ground contacts
- Support 500 bits/sec. "broadcast" telemetry mode
- No C&DH data compression is required

C&DH Requirements vs. TIMED

Feature	TIMED	STEREO	Software Impact
H/W redundant?	Yes	No	Requires new S/W loading approach
GPS?	Yes	No	Requires new timekeeping software
# Instruments	4	6-7	More 1553 remote terminals to manage
RS-422?	No	Yes	New driver needed; high speed I/O changes system scheduling and timing
Max science rate	55 kbps	450 kbps	Higher max. recording rate decreases flexibility in SSR management
Max downlink	4 Mbps	800 kbps	Lower max. downlink rate increases flexibility in SSR management
Broadcast?	No	Yes	New software needed to collect broadcast data, select between

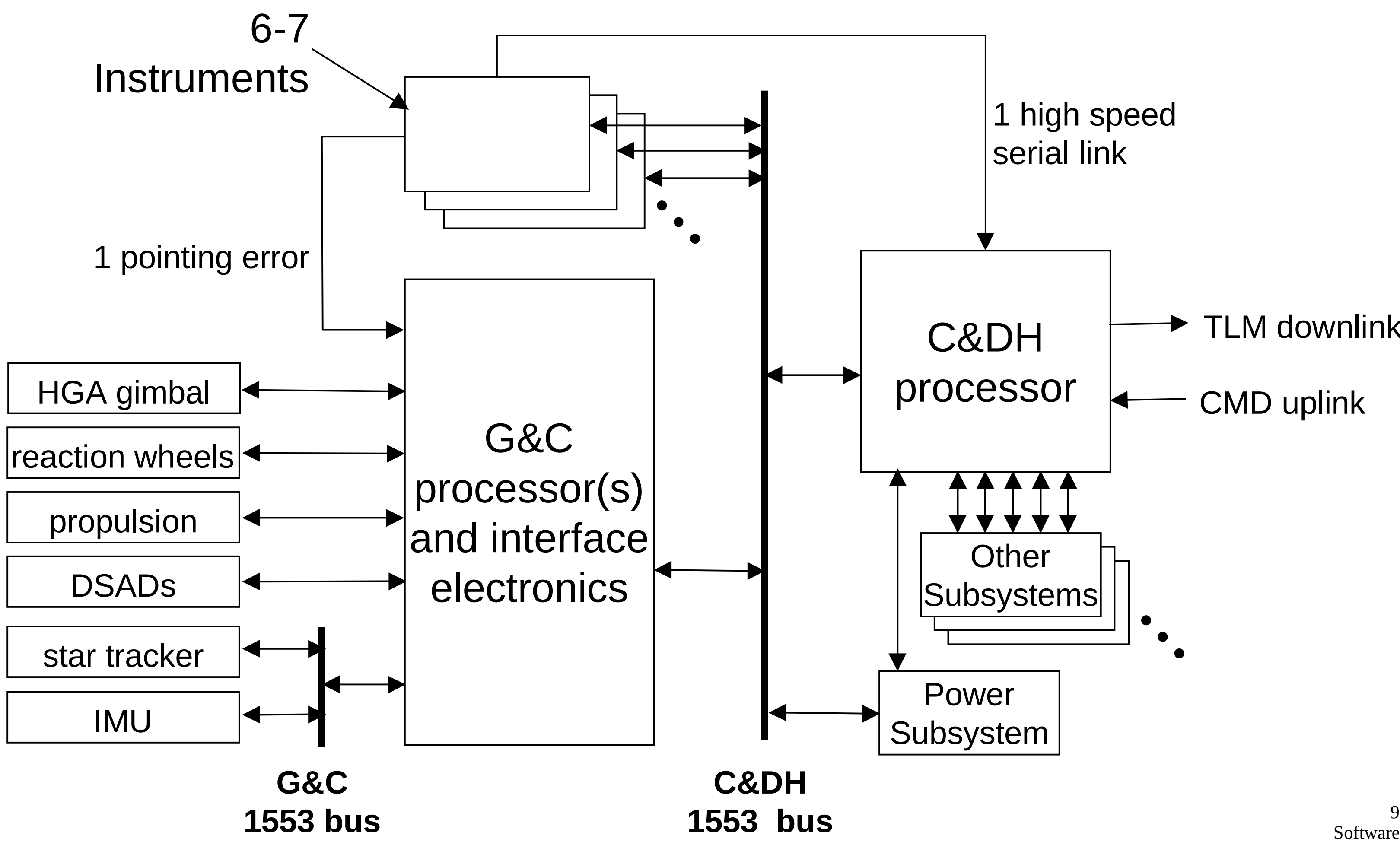
G&C S/W Requirements

- Maintain spacecraft attitude safety
- Support spacecraft operational requirements
  - High gain antenna pointing
  - Solar panel alignment
  - Autonomous momentum management
- Support instrument requirements
  - Maintain solar pointing within long term and jitter specifications
  - Provide Sun keep-in violation, momentum dump warnings
- Generate G&C system telemetry
  - Attitude history
  - Anomalous event dumps
  - Routine G&C status and health reports

G&C Requirements vs. TIMED

Feature	TIMED	STEREO	Software Impact
H/W redundant?	Yes	No	Requires new S/W loading approach
GPS?	Yes	No	Requires new orbit determination software
Momentum management	Torque rods	Cold gas	Requires new I/O and control software
Star tracker, IMU, etc.	Known	TBD	Requires new I/O and control software if devices differ from TIMED
High gain antenna	No	Yes	Requires new I/O and control software for gimbal
Error signal	No	Yes	Requires new I/O and control software
Control update frequency	10 Hz	TBD	Unknown until further analysis; could help or hurt processor margins

Flight Software Environment



C&DH Software Baseline

- TIMED architecture
  - Reuse requirements document as starting point
  - 12 MHz Mongoose running Nucleus+ RTOS
  - Same approach to uplink, downlink, 1553 bus management
  - Add drivers for RS-422 high speed link
  - Delete instrument daily packet quota enforcement
  - Power management requirements TBD
- Load estimates
  - CPU usage: 25% (based on TIMED estimates updated for STEREO)
  - Memory: TIMED is under 30% usage of code space (RAM and flash), assuming 50% of memory is available for code

G&C Software Baseline

- TIMED software architecture
  - 12 MHz Mongoose running Nucleus+ RTOS, with RTX2010 based Attitude Interface Electronics
  - Reuse requirements documents as starting point
  - Eliminate attitude processing in AIE to reduce complexity and regain processor and memory margin
  - Use RTW again to automatically generate attitude “c” code for GCC
- Load estimates
  - CPU usage: AIU usage about 25%; GCC unmeasured
  - Memory: TIMED AIU uses over 85% of RAM; GCC uses <30% of RAM allocated for code

I&T S/W Requirements

- Deliver commands to S/C and instruments at bench system
- Assess and archive spacecraft telemetry
- Deliver instrument telemetry to instrument teams
- Provide visibility into internal spacecraft interfaces for test purposes
- Support multiple hardware configurations as integration proceeds
- Support test scripting, data collection, and problem reporting and resolution

Mission Operations S/W Requirements

- Deliver and log commands for two spacecraft and their instruments
- Receive and distribute all downlink telemetry
- Monitor spacecraft health and safety
- Assess and archive spacecraft telemetry data
- Produce and distribute time correlation and navigation data
- Maintain spacecraft command and telemetry dictionaries
- Support spacecraft activity planning
- Maintain configuration control of uploadable software and parameters

Mission Operations Requirements vs. TIMED

Feature	TIMED	STEREO	Software Impact
# spacecraft	1	2	Requires separate command and telemetry databases, sorting commands and telemetry by spacecraft, and supporting 2 passes simultaneously
Ground station	APL/ LEO-T	DSN	Requires changes to contact planning
GPS?	Yes	No	Requires ground-based navigation team with interfaces to DSN
Unsupported passes	Goal	Weekend	Requires up-front commitment to more automated operations

GSE Software

- G&C testbed
  - Connects to G&C computer; accessible via Ethernet
  - Simulates G&C system components and environment
  - Allows real time closed loop tests of the attitude system
  - Becomes part of the real time spacecraft simulator after launch
- C&DH testbed
  - Connects to C&DH computer; accessible via Ethernet
  - Simulates C&DH interfaces and environment
  - Allows real time tests of C&DH hardware and software

GSE Software (con't)

- Mini-MOC (if implemented)
  - Is a stripped-down version of the MOC, available early in the program, for use in G&C and C&DH subsystem testing.
  - Can command and receive telemetry from both the subsystem under test and supporting GSE
  - Uses the same command and telemetry dictionaries, command procedures, and display pages as the MOC
- Spacecraft emulator (if implemented)
  - Accessible via Ethernet
  - Connects to instruments via their spacecraft interfaces (1553, serial)
  - Emulates spacecraft functions that support instruments
  - Allows instrument checkout before spacecraft integration
  - TIMED provided one emulator to each instrument developer

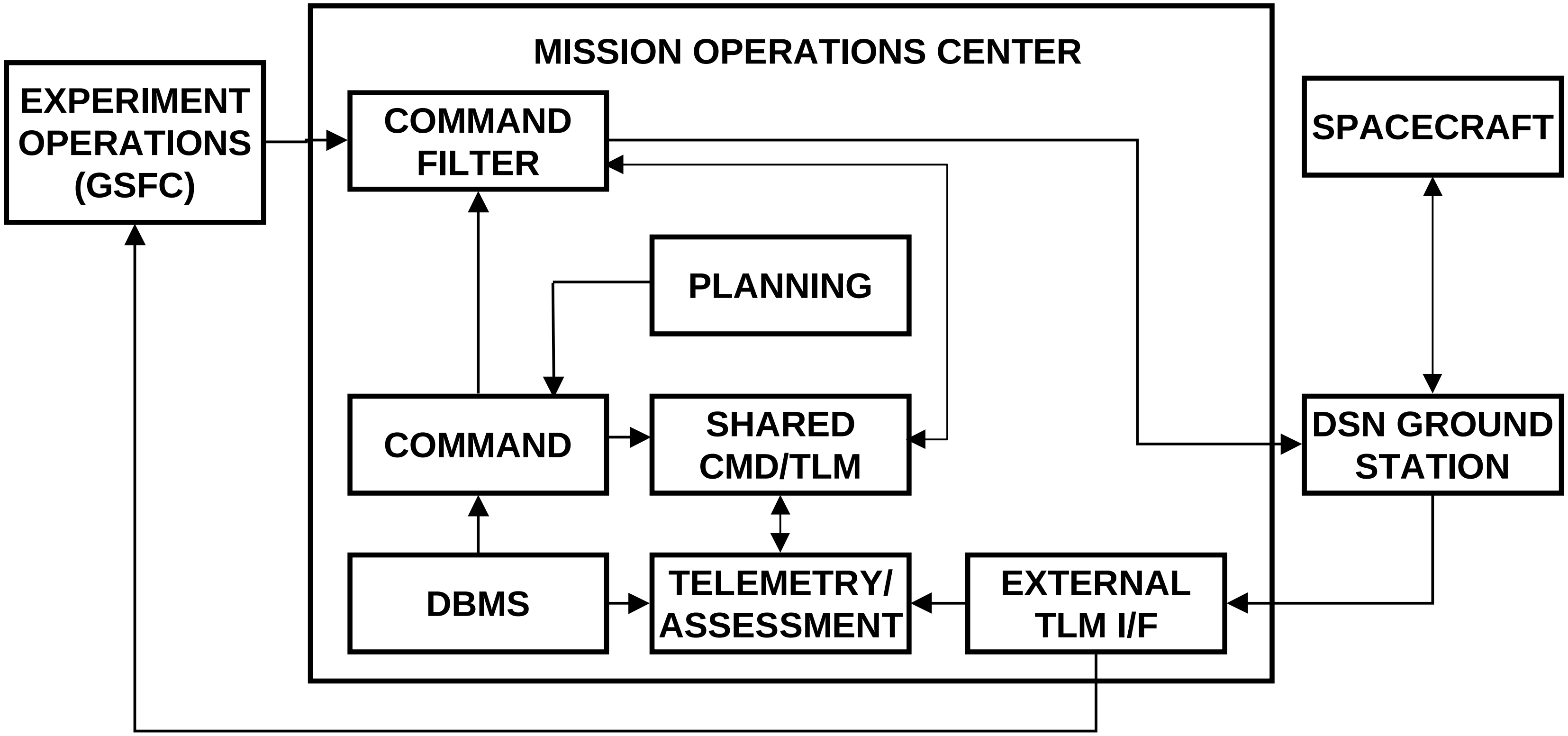
Trade Studies for Phase A/B

- Elimination of the processor in the AIE
  - G&C computer would manage all attitude tasks
  - Trade study must ensure the G&C computer would not be overloaded
  - TIMED AIE boot and application software were costly
  - AIE's RTX 2010 development tools are no longer supported
- Selective SSR playback to allow direct replay of missed transfer frames without playing back a whole segment
- Use of variable length packets
  - Study whether benefits of variable length packets outweigh costs

Trade Studies for Phase A/B (con't)

- Operating systems, tools
  - Nucleus+ (TIMED RTOS for Mongoose), VxWorks, VRTX
  - TASKING (TIMED development tools for Mongoose), gnu
- Use of EPOCH for Mission Operations Center
- Implementation of Mini-MOC, spacecraft emulator
  - Cost/benefit tradeoff

Mission Operations S/W Baseline
(Based on TIMED EPOCH 2000 System)



Technology Insertion Candidates

- Use of commercially available file system extensions to Real Time Operating System
  - Code and parameter upload and download operations become simple file transfers
  - Easy, familiar model for Mission Operations
- Non-coherent Doppler navigation (with JHU/APL-supplied hardware and software at DSN ground stations)
- Unattended weekend operations

RF Communications

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General

- Two-year mission life
- Five-year goal
- X-band TWT A, designed for two-year mission life plus <18 month ground operation.
- Primary DSN resource is existing 34m BWG antenna system, supplemented by 34 m HEF/upgraded 34m BWG and 70 m systems as required

General (con't)

- Simultaneous X-band uplink, X-band downlink and tracking
  - Uplink
    - Normal mode: 125 bps
    - Emergency: 7.8125 bps
  - Downlink
    - Normal high rate science mode: >200 kpbs (when HGA pointing maintained within +0.1°)
    - Broadcast mode: 500 bps
    - Emergency mode: 10 bps

Uplink and Downlink

- Margin is 3 dB (min); 6 dB goal on uplink
- BER ≤10E–6

Downlink

- High Rate Science
  - 5 Gbit downlink per DSN contact for two year mission life:
    - Translates to 200 kbps in 7-hr downlink time
    - At two years distance from Earth for baseline trajectory:
      - –Leading spacecraft (drift rate 20°/yr) is at 0.65 AU
      - –Lagging (drift rate 28°/yr) is at 0.97 AU
    - DSN resources are 34 m BWG antenna system supplemented with 34 m HEF and 70 m
    - Post launch/early operations 800 kbps max
  - Rate 1/6, k = 15 convolutional coding + RS
  - Bit rate spacing 3 dB (nominal)

Downlink (con't)

- Broadcast mode:
  - 500 bps downlink rate:
  - R = 1/2, k =7 convolutional coding + RS
  - No uplink
  - X-band baseline:
    - Data downlinked through spacecraft HGA
    - TBS ground system, G/T is specified based on link
- S-band option:
  - Data downlinked through spacecraft dual feed X- and S-band HGA
  - NOAA ground system
- Emergency operation:
  - 34 m HEF and 70 m DSN resources

Navigation Support

- Navigation support via two-way Doppler tracking using JHU/APL developed non-coherent tracking technique:
  - For the two year mission support:
    - 0.1 mm/s (over 60 sec measurement interval) Doppler accuracy
    - $\pm$ 7500 km position accuracy
  - JHU/APL develop software. Where software resides (JHU/APL or JPL/DSN) will be negotiated with DSN during Phase A.
  - DSN provide to JHU/APL:
    - Product (raw Doppler information) from Radiometric Data Center
    - All spacecraft telemetry frames, frame number, frame synchronization time tags (a standard product)

RF Communications

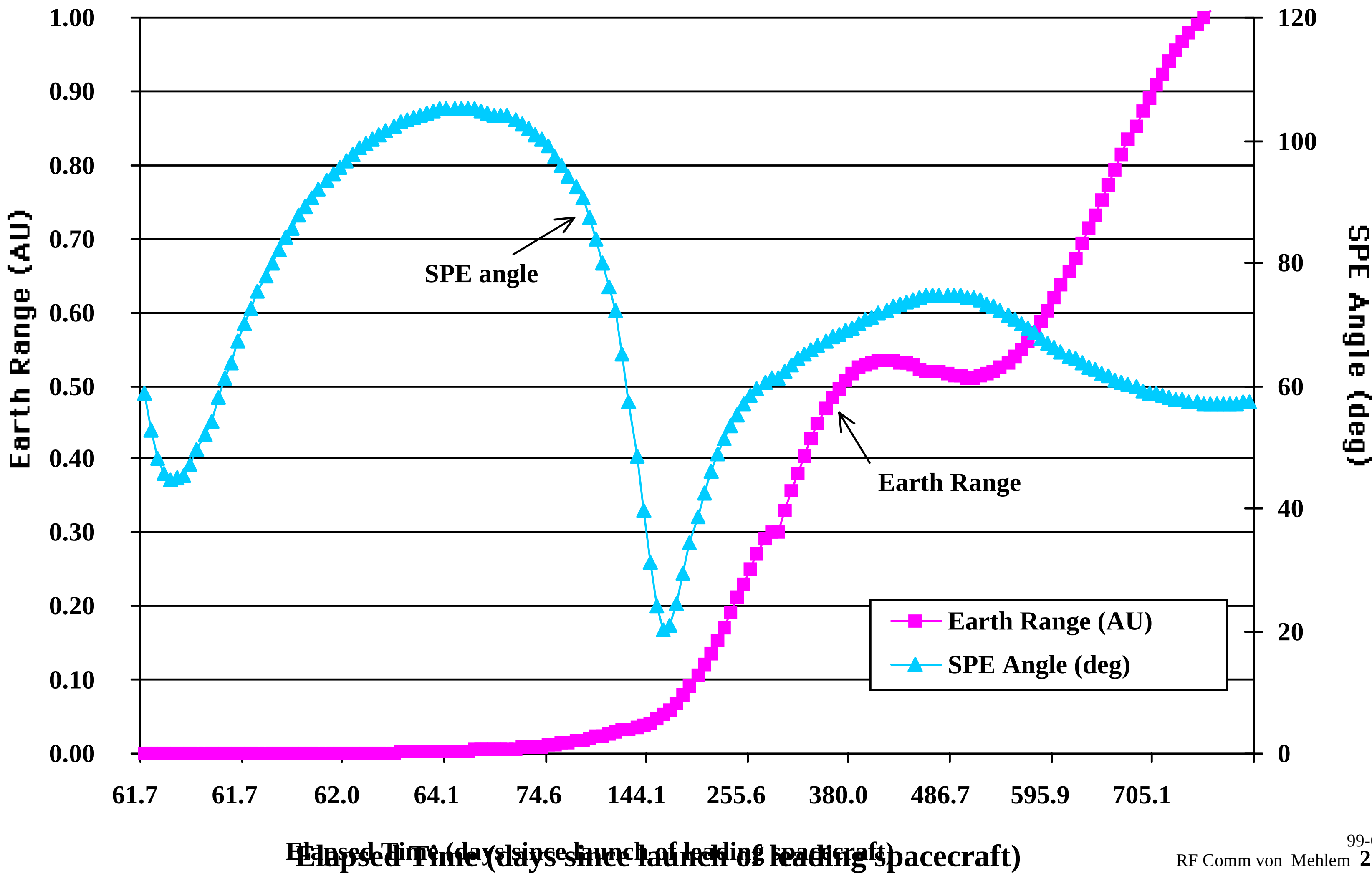
Additional Information -
Preliminary Downlink Bit Rate Performance

Judi von Mehlem

Solar Terrestrial Relations Observatory (STEREO)
Pre-Phase-A Requirements Review

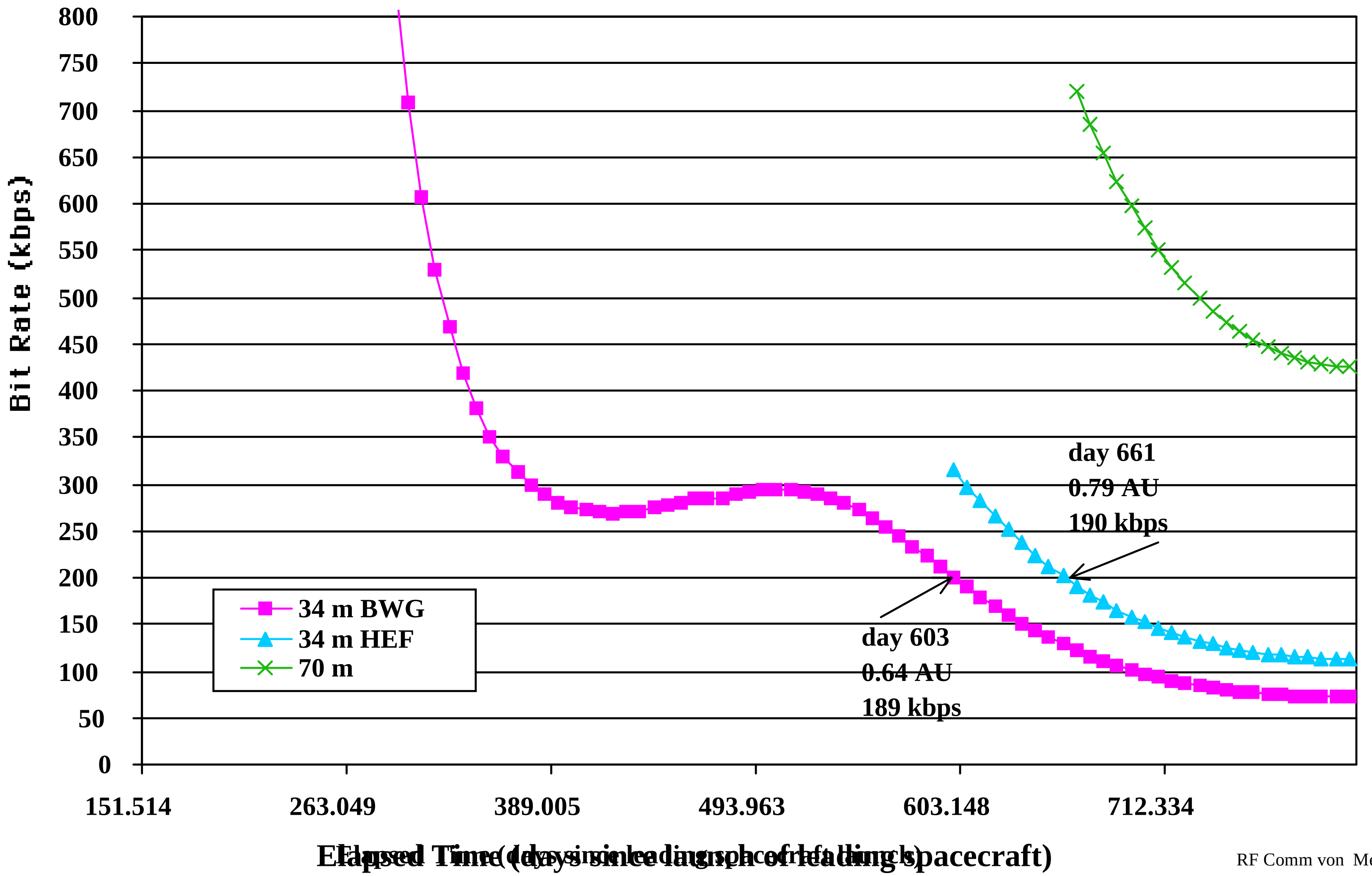
STEREO 28 deg/year Lagging Spacecraft

Earth Range and Sun-Probe-Earth Angle vs Elapsed Time since Leading S/C Launch



Solar Terrestrial Relations Observatory (STEREO)
Pre-Phase-A Requirements Review

STEREO 28 deg/year Lagging S/C
Bit Rate Capability S/C HGA to DSN Resources
(Preliminary)



Bit rate performance deficiency summary for 28 deg/yr lagging spacecraft
(Baseline is 40 W TWTA; 1.1m HGA; 3 dB link margin)

DSN antenna system	S/C HGA (m)	TWTA (w)	Day[1]	Earth Range (AU)	Bit Rate (kbps)	Link Margin (dB)
Last ~131 days						
34m BWG	1.1	40	603	0.64	189[2]	3
	1.1	40	603	0.64	200	2.7[2]
	1.1	40	668	0.81	115	3
	1.1	40	734 (2 years)	0.97	82	3
	1.75	40	734	0.97	200	3
34m HEF	1.1	40	661	0.79	190[2]	3
	1.1	40	734	0.97	128	3
	1.1	40	734	0.97	200	1
	1.4	40	734	0.97	200	3
	1.1	60	734	0.97	200	2.8[2]
70 m	1.1	40	734	0.97	485	3

Table notes:

1. Relative to launch for leading spacecraft (60 days earlier than lagging spacecraft)
2. Bit rate close to 200 kbps or margin close to 3 dB, within calculation assumptions for prephase A

- **28 DEG/YEAR LAGGIN SPACECRAFT TABLE ASSUMPTIONS:**
  - **SPE angle is <105 deg throughout mission. SPE is only >90 within first 25 days of launch of lagging spacecraft. HGA is used for downlink when SPE<90 deg. Extended HGA (with 2 dB degradation) is used for SPE between 90 and 105 deg.**
  - **Existing 34 m BWG performance is used**
- **CONCLUSION:**
  - **Link does not support 200 kbps using existing 34 m BWG from ~day 603 to ~day 734 (~131 days).**

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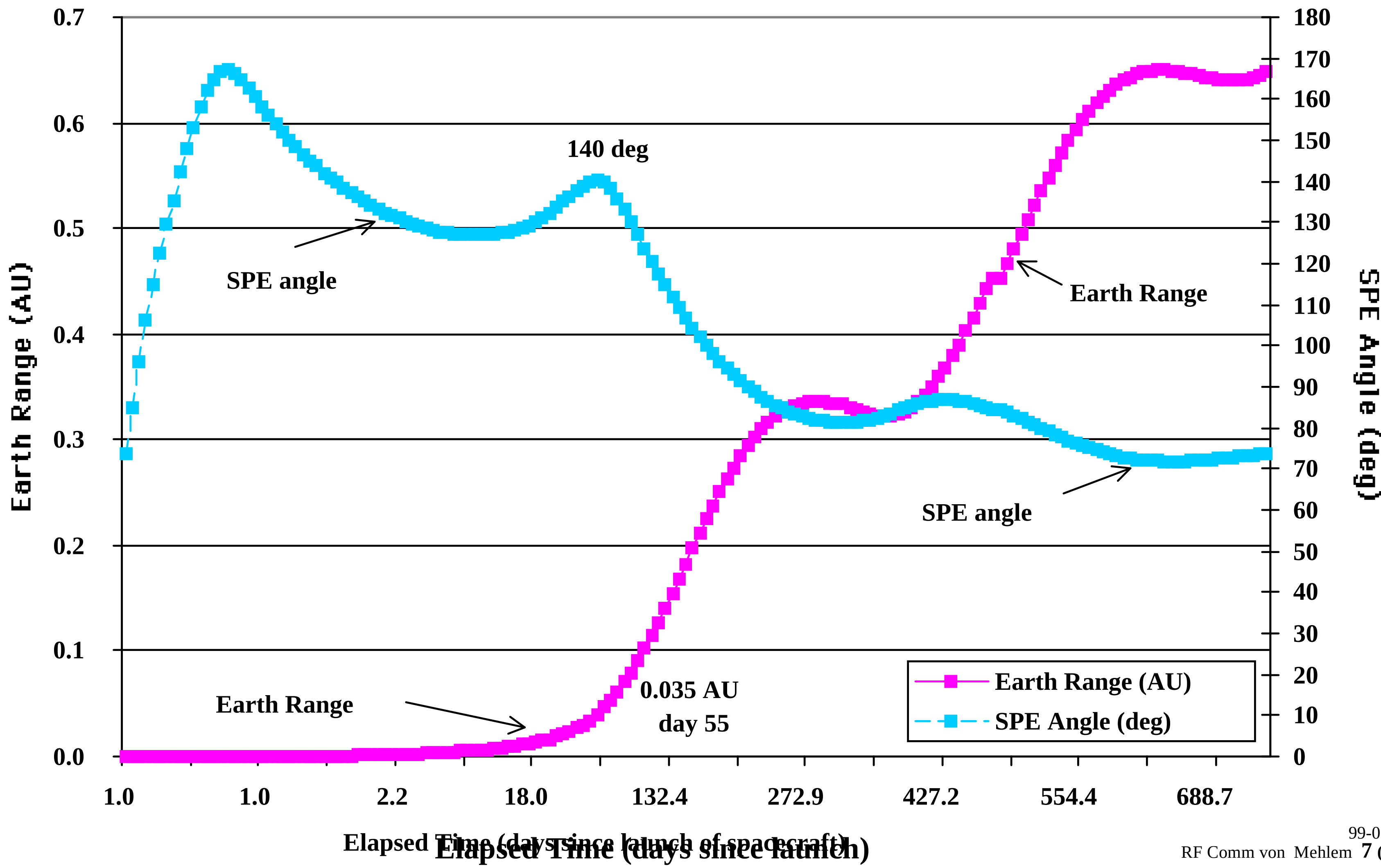
  - **Existing 34 m BWG performance is used**
- **CONCLUSION:**
  - **Link does not support 200 kbps using existing 34 m BWG from ~day 603 to ~day 734 (~131 days).**

- **28 DEG/YEAR LAGGIN SPACECRAFT TABLE CONT:**
- **MITIGATION:**
  - **Increase HGA size (mechanical limitations with present launch vehicle)**
  - **From ~day 603 to ~661 (~58 days) use 34m HEF (if 34m BWG is upgraded, could use it since performance is expected to approach HEF performance). From ~day 661 to ~734 (~73 days) use 70 m DSN system. (cost)**
  - **Increase transmitter power (cost, dc power).**
  - **Accept lower link margin (risk).**

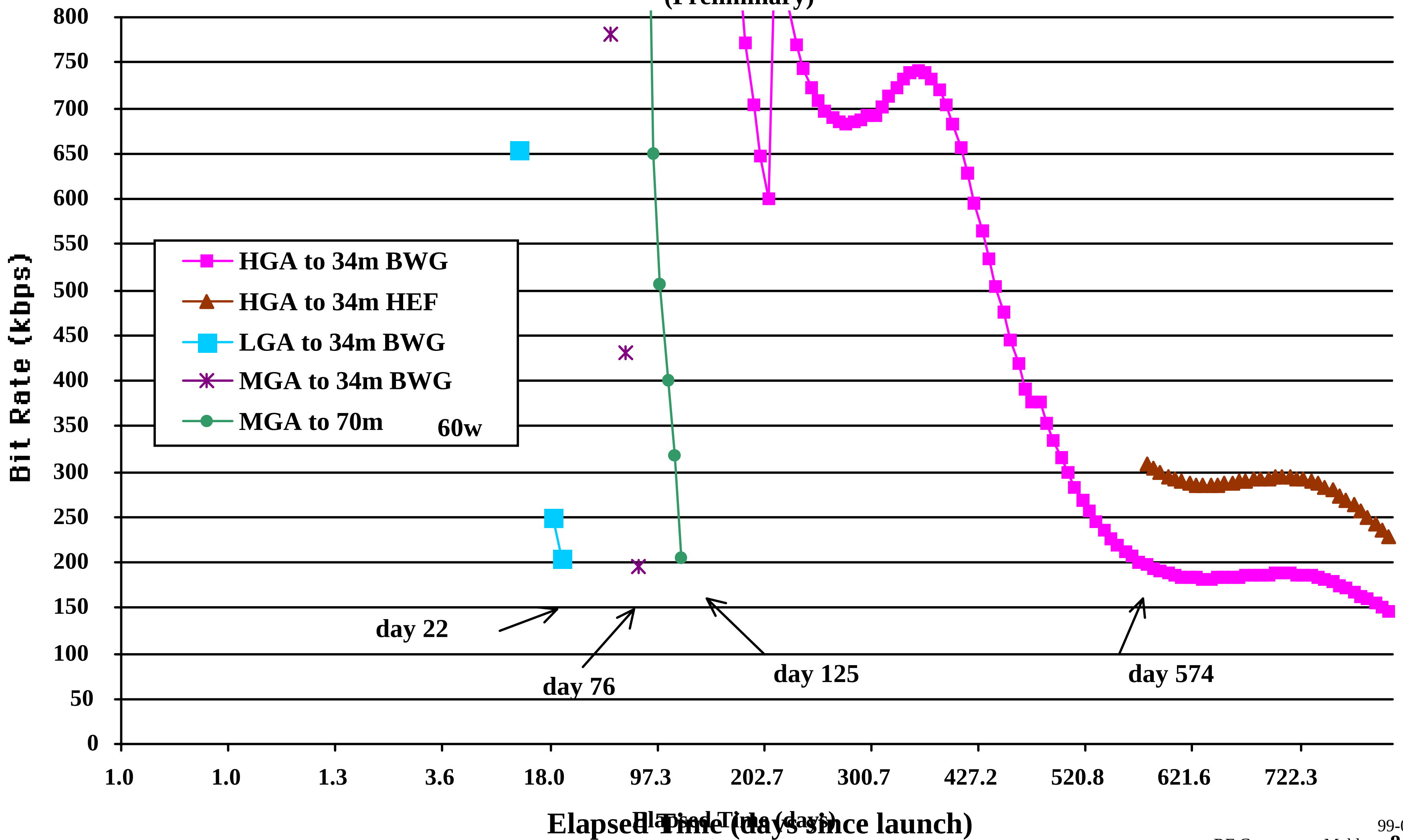
Solar Terrestrial Relations Observatory (STEREO)
Pre-Phase-A Requirements Review

STEREO 20 deg/year Rate Leading Spacecraft
Sun Probe Earth Angle and Earth Range vs Elapsed Time since S/C Launch



Solar Terrestrial Relations Observatory (STEREO)
Pre-Phase-A Requirements Review

STEREO 20 deg/year Leading S/C- Bit Rate Capability S/C HGA to DSN Resources (Preliminary)



Solar Terrestrial Relations Observatory (STEREO)
Pre-Phase-A Requirements Review

Bit rate performance deficiency summary for 20 deg/yr leading spacecraft
(Baseline is 40 W TWTA; 1.1m HGA; 3 dB link margin)

DSN antenna system	S/C antenna	TWTA (w)	Day[1]	Earth Range (AU)	Bit Rate (kbps)	Link Margin (dB)
Last ~ 226 days						
34m BWG	1.1 m HGA	40	574	0.63	196[2]	3[2]
	1.1 m HGA	40	800 (2 years)	0.72	149	3[2]
	1.1 m HGA	40	800	0.72	200	1.75
	1.1 m HGA	60	800	0.72	223	3
	1.3 m HGA	40	800	0.72	200	3.1
34m HEF	1.1 m HGA	40	800	0.72	234	3
Day ~76 to ~125[3]						
34m BWG	MGA	40	76	0.06	196[2]	3
	MGA	40	90	0.08	73	3
	MGA	40	125	0.14	14	3
70 m	MGA	40	111	0.11	336	3
	MGA	40	125	0.14	88	3
	MGA	40	118	0.13	200	1
	MGA	60	118	0.13	200	3

Table notes:

1. Launched 60 days earlier than lagging spacecraft. 800 day mission life envelopes 2 year for mission life for lagging spacecraft.
2. Within calculation assumptions for pre-phase A.
3. SPE is between 115 and 143 deg (~ 20 deg).

- **20 DEG/YEAR LAGGIN SPACECRAFT TABLE ASSUMPTIONS:**
  - **LGA (based on NEAR) is used post launch until ~day 20. MGA (based on NEAR fanbeam) is used ~day 20 to 125. HGA used from ~day 125 through end of mission. SPE is >90 from day 125 to 209.**
  - **Assume spacecraft is oriented about x-axis to maximize antenna gain towards earth.**
  - **Existing 34 m BWG performance is used**
- **CONCLUSION #1:**
  - **Link does not support 200 kbps using existing 34 m BWG from ~day 574 to ~day 800 (~226 days).**

- **20 DEG/YEAR LAGGIN SPACECRAFT TABLE CONT:**
- **MITIGATION:**
  - **Use 34m HEF (if 34m BWG is upgraded, could use it since performance is expected to approach HEF performance).**
  - **Increase transmitter power (cost, dc power).**
  - **Increase HGA size (mechanical limitations with present launch vehicle)**
- **CONCLUSION #2:**
  - **Link does not support 200 kbps using existing 34 m BWG from ~day 76 to ~day 125 (~49 days).**

- **MITIGATION:**
  - **Redesign NEAR fanbeam antenna to provide more gain over smaller beamwidth (mechanical limitations with launch vehicle and spacecraft hardware, cost) or design a new antenna (cost).**
  - **Use 70 m DSN system and higher power (cost, dc power).**
  - **Use 70 m DSN system and accept lower link margin (cost, risk).**
  - **Slew spacecraft to direct HGA at earth (loose science during downlink)**
  - **Redesign trajectory to move second peak of high SPE earlier in mission (may not be possible, science impact).**
  - **Have second small (~9 in) gimballed dish (mechanical constraints on spacecraft, costly.**

Orbit Determination

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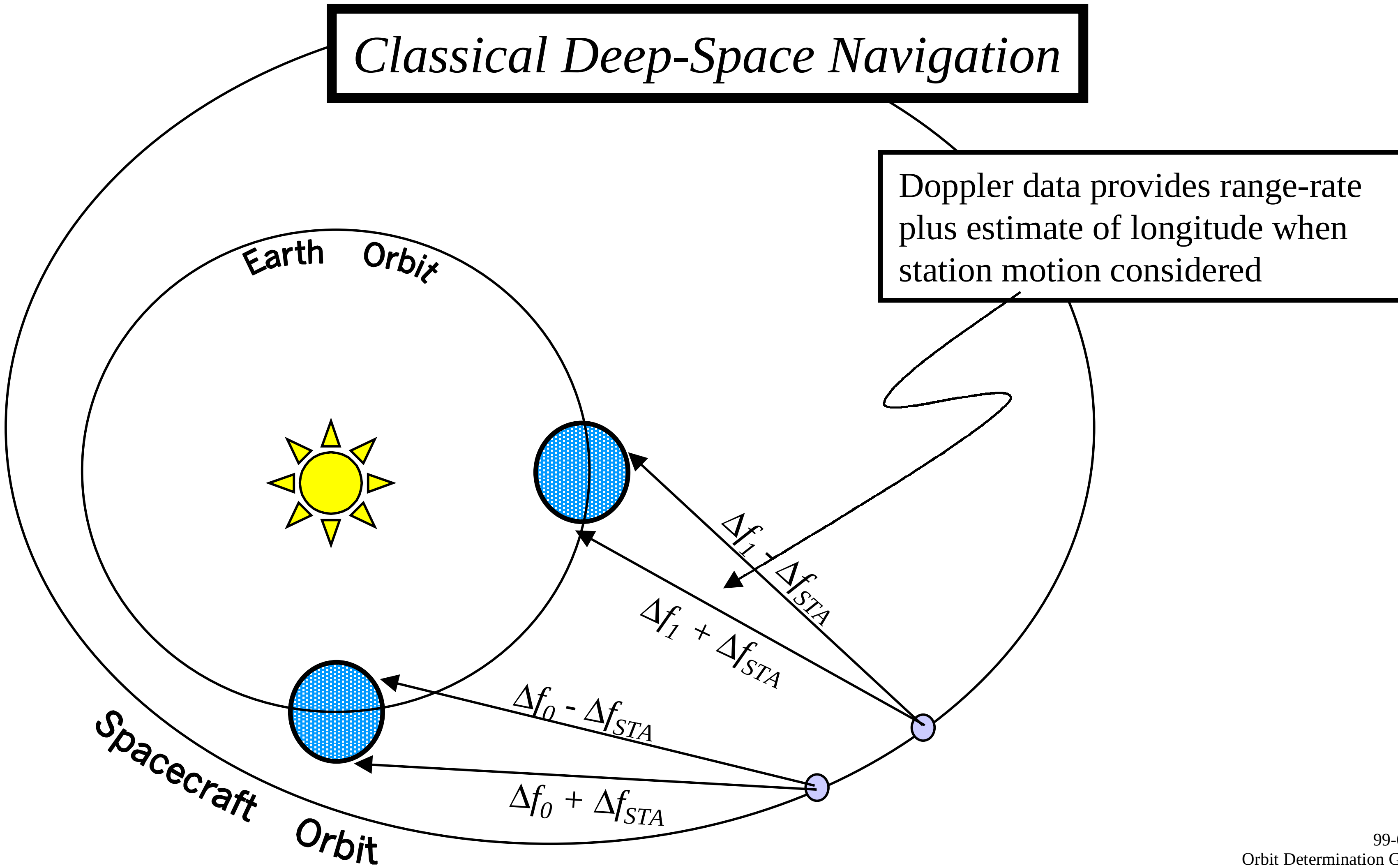
Navigation Characteristics

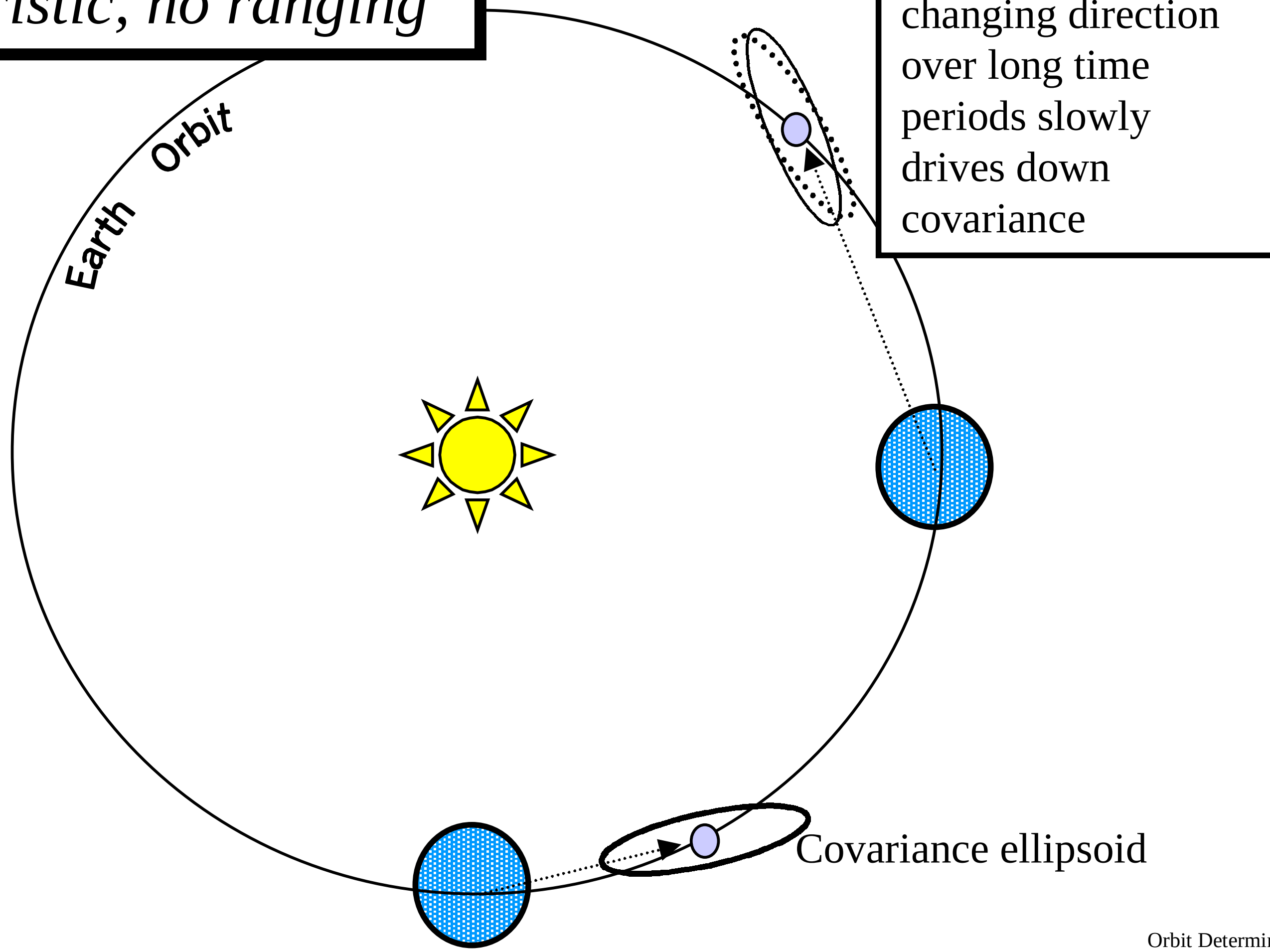
- Singular Doppler data provides range-rate (0-D solution)
- Station motion over one day provides 1-D solution (longitude)
- Add ranging to produce 2-D solution
- Add N/S stations or solar angles to get 3-D solutions
- Need change in Doppler data over time
  - STEREO in nearly identical Earth orbit
  - Fitting arcs very long (weeks or months)
  - Hi-fidelity radiation pressure model needed
    - Need dynamic cross-sectional area model
    - Need attitude information

Solar Terrestrial Relations Observatory (STEREO)
Pre-Phase-A Requirements Review

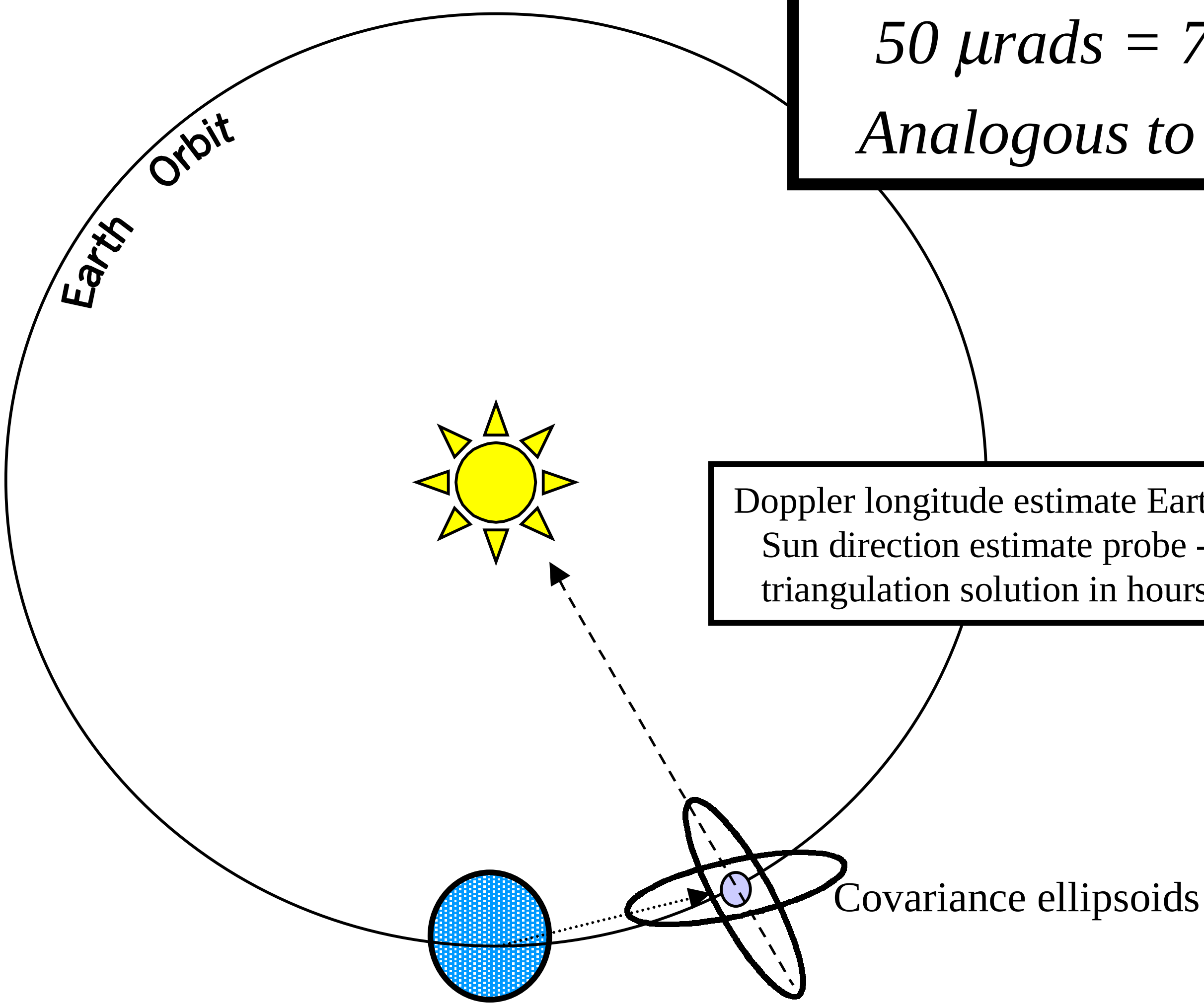


Solar Terrestrial Relations Observatory (STEREO)
Pre-Phase-A Requirements Review

STEREO Nav
Characteristic, no ranging



Doppler with sun angle,
50 μrads = 7500 km
Analogous to ranging



Doppler longitude estimate Earth --> probe plus Sun direction estimate probe --> Sun yields triangulation solution in hours or days

Spacecraft Sun Angle Experimental Data

- Triangulation method determines Earth –> probe range
- Convergence time drops from weeks/months to hours/day
- Minimizes need for hi-fidelity radiation pressure model
- Possibly good to 50 μrads, would meet 7500 km requirement
- Inclusion in ground processing filter
- Needed for any onboard autonomous nav experiments

Navigation Ground Software

- Acquire/[modify] existing systems
- Have narrowed candidates down to:

  GTDS–Goddard Trajectory Determination System
  OCEAN–Orbit Covariance Estimation and Analysis

- Currently determining capabilities of each
- TBD–ease of modifiability

GTDS–Goddard Trajectory Determination System

- Old reliable, currently used on ~40 missions
- Vintage 1970's, batch, mainframe, Fortran, card punch format
- Installed and tested on JHU/APL Unix machines
- Source code, makefiles transmitted to JHU/APL, no known license problems
- Documentation delivered
- Ephemeris generator, orbit determination, test generation modules
- Hi-fidelity solar system and atmospheric models
- Determine modifiability

OCEAN–Orbit/Covariance Estimation and Analysis

- Developed by Naval Research Lab (circa 1995, ongoing)
- Backup support for 12 operational LEO satellites (automated)
- Executable and documentation (no source) provided to support TIMED Guidance and Navigation System (GNS) validation
- Supported on DEC (VMS, Ultrix) and SGI (IRIX)
- Batch or filter based estimation (method is observation type dependent)
- Hi-fidelity solar system and atmospheric models
- Determine modifiability

Conclusions

- Assume ‘one-way non-coherent’ Doppler
- Require Doppler data (range-rate) product
- Require RF ranging product (especially early in mission)
- Require solar angle (SCIP centroiding data) plus S/C attitude for alignment calculations and navigation option
- Require orbit determination software support
  - Baselining GTDS or OCEAN
  - Steep learning curve
  - Installation, testing, enhancements
  - Interface software development